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Survey on Biomass Drying Process

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Declaration

I declare that the presented bachelor´s Thesis entitled “Survey on Biomass Drying Process” is done as my own work and effort with use of the referred literature. I agree with the storage of this work in the library of CULS in Prague and making it available for further study purposes.

In Prague ………………

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Vojtěch Marek

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I would like to express my appreciation to everyone who helped me with the work on this thesis. With special thanks belonging to Ing. Tatiana Ivanova, Ph.D. for her broad assistance and detail consultancy. Special thanks also belonging to Prof. Ing. Bohumil Havrland, Csc, who have gave me possibility to realize such an interesting Thesis from the beginning until the hanging in. From the Moldavian side, thanks to Msc. Alexandru Muntean (State Agrarian University of Moldova, Chisinau) for realization support of the practical work with thanks to all the students and tutors helping me to gain the precise and valuable data.

ABSTRACT

The main objective of the present work is to analyze the biomass drying process in experimental dryer with solar collector in State Agrarian University of Moldova, Chisinau. Use of drying technology in general might be seen as a way to obtain an alternative energy source and this concept has its potential for the developed countries as well as it is applicable for the so-called countries of global south.

The methodology of the Thesis is following. In theoretical part the brief overview of the drying techniques is presented with a look at the case of energy sustainability. The data of practical part are collected. The values of moisture content and air parameters (temperature, relative humidity and speed) are measured in different selected places located in the dryer and primary inside the biomass layer. For the period of 13 days of drying process the parameters of energy crop topinambour (*Helianthus tuberosus l.*) were measured according to standard. Analyses of results are included.

The results show that the drying of biomass is uneven over the different locations of the dryer and inside the material; this is presented in the model of moisture trend development. High heat losses were found in the experimental drying system which is radically lowering the temperature in mixing chamber and is advised to be upgraded. The most valuable result is that the mixing of material during the drying process is beneficial technique for the overall process of drying. Mixing contributes to more even, efficient and faster drying. Recommendations for improvements to the structural design of the dryer are listed at the end of the work.

Key words: biomass, solar dryer, moisture content, air humidity, temperature, topinambour, collector

ABSTRAKT

Hlavním cílem práce je analýza procesu sušení biomasy v experimentální sušičce se solárním kolektorem na státní zemědělské univerzitě v Moldávii. Využití sušičky lze jednak chápat jako nástroj po získání alternativního zdroje energie ve vyspělých zemích, nebo jako vhodnou alternativu sušení v zemích takzvaného globálního jihu.

Metodika práce je následující. V teoretické části je kladen důraz na techniku sušení a je prezentována z pohledu energetické udržitelnosti. V praktické části jsou shromážděna potřebná data - hodnoty vlhkosti materiálu a parametrů vzduchu (teplota, relativní vlhkost a rychlost), které jsou monitorovány v různých vybraných místech v sušičce a hlavně uvnitř vrstvy biomasy. V rozmezí třinácti dnů jsou tyto parametry na přiklade energetické plodiny topinambur (*Helianthus tuberosus, l.*) měřeny v souladu s normou. Analýza výsledků je prezentována v závěru práce.

Výsledky ukazují, že sušení biomasy neprobíhá rovnoměrně napříč sušickou a sušeným materiálem, více je vyobrazeno v modelu změny vlhkosti. Velký pokles teplot je zjištěn v mísící komoře, odkud je ohřátý vzduch hnán k sušenému materiálu. Tento teplotní pokles by měl být brán v potaz. Nejcennějším zjištěním se ukázala potřeba míchání materiálu během procesu sušení. Míchání přispívá k rovnoměrnějšímu, efektivnějšímu a rychlejšímu sušení. Doporučení pro vylepšení konstrukčního řešení sušičky jsou uvedeny na konci práci.

Klíčová slova: biomasa, solární sušička, vlhkost, vlhkost vzduchu, teplota, topinambour, kolektor

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List of Abbreviations

Approx. - approximately

ČSN – Czech Technical Standards

FAO – Food and Agricultural Organization

Grnd – ground

HDI – Human Development Index

MDG – Millennium Development Goals

PJ – ‘petajoule’ (equal to 1015 J)

T – temperature [°C]

φ – humidity (%)

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1. Introduction

There was always tension to over control the source of energy to overcome the rising of energy consumption. How do we solve it?

… ‘PERPETUUM MOBILE,’ a machine creating its own motive power.

Nicola Tesla, The Problem of Increasing Human Energy (1900)

With no consideration of citation putted out of context by Nicola Tesla; according to the second and third Newton`s law we fully reject “perpetuum mobile” as a solution of energy dependency.

However, Prof. Donald in his book Biomass for Renewable energy, Fuels and Chemicals (1998) is also talking about the increasing of energy together with important peak of human history – Industrial Revolution; approx. 1800. Since that time, global biomass distribution has rapidly changed. Biomass use is proportionally decreasing with hunger of fossil fuels on the planet. By author, it is called ‘the Fossil Fuel Era’. The point of Industrial Revolution is crucial not only for biomass use nor for the increasing of fossil fuel consumption but rolls together much more negative foretaste. All this is balanced by positive minds of societies of the so-called developed countries. But on the other side of the World, that time, there was no idea of the coming troubles (Donald, 1998), even in general. Both sides of the worlds are run by the constant growth, indirectly supporting the consumption of fossil fuels (Sedláček, 2013).

Through the last decades, due to the increase of the energy prices run by high demand, energy consumption is topic to talk about. Today, energy consumption is also important to consider from the side of so-called global south countries. There is our responsibility from one hand to deal with the post colonialism and provide to these countries support in the form of knowledge and understanding of the best known technology reachable to the locals (Reid, 2011). On the other hand it is an indirect way to prevent the food loses. For example, El-Sebaii and Shalaby (2011) have concluded that loses of fruits and vegetables during the drying process are about 30 to 40 % of total production.

“These post-harvest loses may be reduced drastically by using well-designed solar drying system” (El-Sebaii and Shalaby, 2011).

Therefore, we believe, that more research in the field of Drying technologies has to be taken in account due to following consequences:

Natural and artificial subjects are increasingly focusing on energy consumption and prices, due to sustainability and efficiency with higher cost of energy itself, respectively (Dam, 2012; Demirbas et al., 2009). However, the case of decreasing fossil fuel consumption should be also reflected for the countries of so-called global south. The reason is caused by the fact that energy is not unlimited source in the World. According to Millennium Development Goals, it is supposed to preserve the energy and look for new resources, ensure the environmental sustainability (Ban, 2013). This fact leads us to the point of consideration of alternative sources of energy.

Plant biomass has a huge potential as an energy source due to its easy reachability and fast recovery ability (Demirbas et al., 2009).

The drying of harvested biomass is necessary step to obtain material ready for further elaboration, either for the biomass combustion or for the food-drying process. This is considered under the exclusion of so-called “Bio-Chemical Convention Methods” used in the wet phase for more than 50% of dry matter content (Havrland and Podebinschi, 2011). Therefore, in the dry phase, the reduction of moisture to the safe level is taking place (Murthy, 2009). The step of drying (preparing the material) to its initial stage for further elaboration is crucial point for the quality of the final briquetting, pelleting, if obtained. The quality of final product is therefore derived from the prepared dry biomass mixture.

For the investigation on biomass drying process the experimental solar dryer in Chisinau was chosen to gain data from particular biomass harvested in local botanical garden. The energy crop *Helianthus tuberosus* (Topinambour) spp. *Asteraceae* was harvested and crushed into smaller pieces. This was done for comparison of previous sub-experiment on drying efficiency of Ing. Tatiana Ivanova, Ph.D, (2012). To propose new ideas and implementations of the experimental solar dryer in Chisinau, the experiment was done under the same conditions with the same methodology commented before by Havrland and Podebinschi in monograph Biomass Processing to Biofuels (2011).

2. Literature Review

The biomass as a renewable source of energy has huge potential shown in practice by Demirbas et al. (2009), it is seen that the combustion of biomass may be used to generate electricity by more sophisticated technology fully supplying the major sources of energy – fossil fuels, for example. By beginning of 18^{th} century, starting with Industrial Revolution time called by Donald (1998) ‘the fossil fuel era’. There is strong correlation with the ecology, CO_2 emissions, etc.

On the other hand, biomass open burning is mostly reachable, and might be the only way for countries of so-called ‘Global south’. The first significant difference, in drying techniques, of the traditional way is lack of indirect drying. Therefore it is also important to take in account different biomass drying techniques. However, further steps (as briquetting and analysis of the product) are out of the drying process and not involved in this Thesis. More about the drying technologies is written in the Chapter 2.2 with comparison of diverse sources.

2.1 *Biomass as (renewable) source of energy*

The biomass potential is also mentioned by Demirbas et al. (2009) and there is shown the actual use of biomass compared to potential between regions of the World. It is shown that only about 40% of the potential biomass energy is being used across the continents (see Table 2.1).

Table 2.1: Biomass potential and use distribution between regions (Source: Demirbas et al., 2009).

Biomass potential (10^3 PJ/year)	*North America*	*Latin America*	*Asia*	*Africa*	*Europe*	*Middle East*	*Former USSR*	*World*
Woody biomass	12.8	5.9	7.7	5.4	4.0	0.4	5.4	41.6
Energy crops	4.1	12.1	1.1	13.9	2.6	0.0	3.6	37.4
Straw	2.2	1.7	9.9	0.9	1.6	0.2	0.7	17.2
Other	0.8	1.8	2.9	1.2	0.7	0.1	0.3	7.6
Total potential	19.9	21.5	21.6	21.4	8.9	0.7	10.0	103.8
Use	3.1	2.6	23.2	8.3	2.0	0.0	0.5	39.7
Use/potential (%)	**16**	**12**	**107**	**39**	**22**	**7**	**5**	**38**

There is an interesting to see that the use of all the biomass resource world-wide not yet explored, only the Asia is using the energy over its annual potential. The low potential use of biomass energy in Europe compering to its human density might be possibly also caused by import of wood from Latin America etc. In Africa, there is a reasonable part of the energy used in traditional way especially in rural areas (Skytte et al., 2006).

„Renewable energy resources do not form an important role in energy resources present [in sense of gross domestic consumption]“ (Jeníček and Krepl, 2008). However, according to Demirbas A. (2005) there is a huge potential of this energy for the future. The author says that biofuel type of energy is the best way of implementation in developing countries for the sustainability and also for the developed countries as a well source of energy. It is needed to concrete the field of biofuel technics to the drying processes of biomass. „ ... *combustion is responsible for over 97% of the world`s bio-energy production*“ (Demirbas A. , 2005). Therefore use of biomass energy in this form is crucial topic to look at.

2.1.1 Traditional and convention drying techniques

Description of different solar drying techniques is shown in this chapter. Mostly all these techniques are indeed leading to the sufficient stage for future either, combustion or pelleting / briquetting of the product. The only example of no combustion taking in apart is drying for the purpose of food conservation, storage or transport (Amer at al., 2010). The importance of the drying stage is necessary before taking any other steps mentioned above.

With decreasing of the moisture, net calorific value of the material increases. This is indirectly caused by lowering the total mass. In theory, by vaporizing of water from the biomass during the combustion process more energy is spend and therefore less energy is gained as an outcome. These consequences are facing to make the drying process sufficient to concern the following efficiency of dried biomass to its peak. The goal is to input enough energy and evaporate water out up to its sufficient moisture to drying efficiency balance (Ekechukwu and Norton, 1999).

From the economical point of view, the drying time is also an important factor to consider at the end for evaluation used for example by Banout at al. (2011) for calculation of payback period for Double-pass solar drier. The solar crop or wood drying is great compromise between the traditional wood and fuel burning and open air drying

(VijayaVenkataRaman et al., 2012). First of all there is traditional open air drying to discuss. Before that, we would like to mention the actual distribution of energy in general.

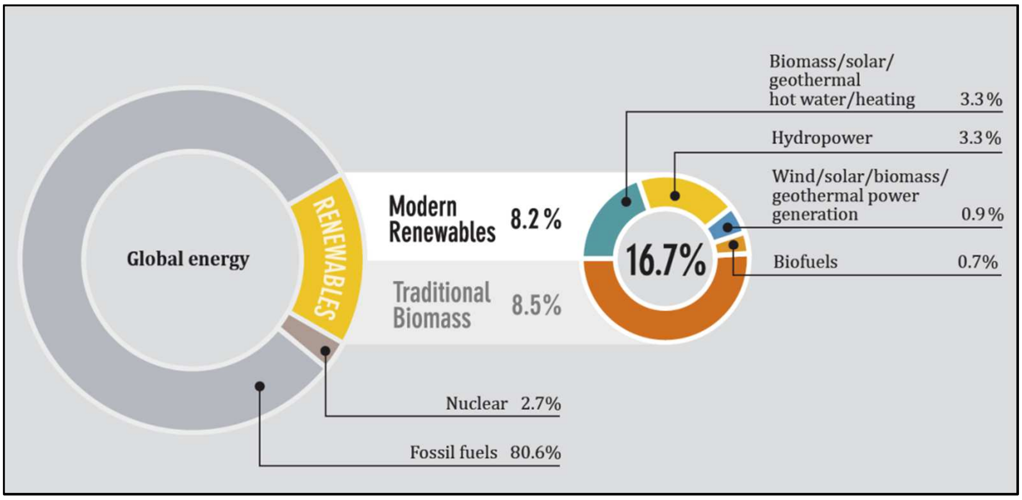

Figure 2.1: Renewable energy resource distribution globally (Source: Global Status Report, 2012)

From the Figure 2.1, there is seen that the traditional biomass energy contribution is than 8.5 % of the whole energy consumption. It refers approximately to 50 EJ globally. And this is mostly traditional biomass for cooking and heating (Koljonen, 2013; Sims, 2006).

The total share of bio-energy consumption is 8.5 % of the overall World consumption (Demirbas A. , 2005), however if the combustion of residuals is considered separately, only a small fraction is made from solar dryer to be used as a source of energy.

To take into account the degradation of biomass quality the results of VijayaVenkataRaman et al. (2012) were used. There are many factors of degrading the quality of biomass during the sunlight drying caused by (1) insect infestation, (2) enzymatic reactions, (3) microorganism growth and (4) mycotoxin development. And Amer et al. (2010) add up to it that during the drying is attacking the biomass also dirt, dust and rains. For my side, even frost condensation would be added. On the other hand, Amer et al. (2010) mentions, that traditional way of drying is (of course) cheap and apart from that “[it is using]…convective power of the natural wind”. With the comparison of the convention dryers, for using e.g. wind would be necessary to use extra fan run by electrical power.

Also moreover of the traditional solar drying methods are compared by Pangavhane et al. (2002) to conclude the efficiency differences of this traditional methods and the new solar drying techniques. From his results, there is strongly seen that the solar dryers are at least four times more efficient compare to traditional techniques.

2.1.2 Biomass burning process and the fossil fuels consequences

There is a goal of European Union from 2009 to reduce CO_2 emissions, increase the energy efficiency and share of renewable energy based on biofuels, wind, sun and geo-thermal resources up to 20% in the year 2020. This part will be focused only on the CO_2 emissions; it is not discussed only because of the EU visions but also by the significant weather changes. Ether it is correlated or not with this topic, pressure of lobby does require to do so.

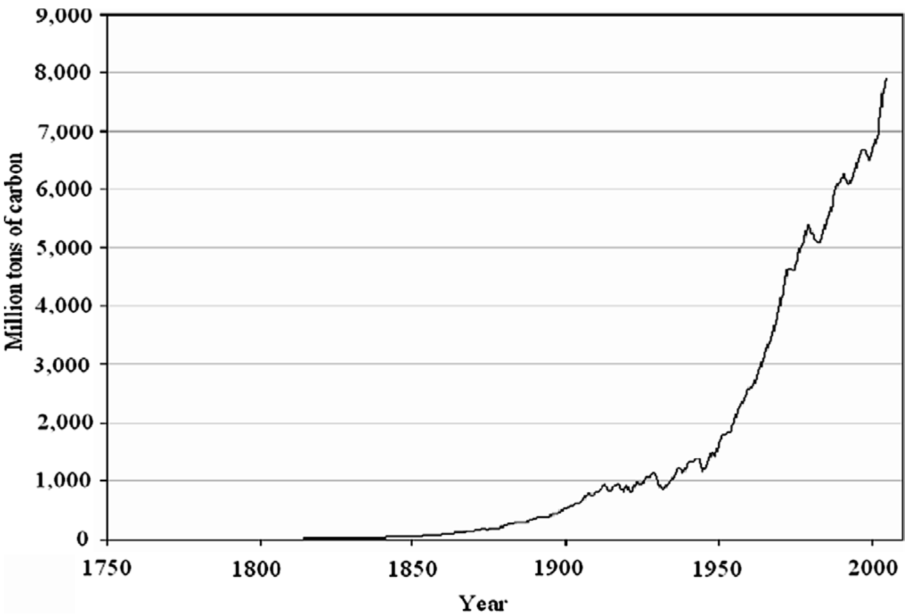

Figure 2.2: Global carbon emissions from fossil fuel combustion between 1951 and 2005, (Demirbas et al., 2009)

From the Figure 2.2 the trend of constant rising of carbon emission approximately since industrial revolution is shown. The trend is well representing to get an overlook of the current global situation. Fossil fuels have net carbon emissions much higher (10 to 20 times) than the emissions from the plants (Sims, 2006). However, this fact is done by the actual amount of CO_2 stored in the plant many years ago.

"Burning fossil fuels uses ''old'' biomass and converts it into ''new'' CO_2; which contributes to the ''greenhouse'' effect and depletes a non-renewable resource. Burning new biomass contributes no new carbon dioxide to the atmosphere, because replanting harvested biomass ensures that CO_2 is absorbed and returned for a cycle of new growth" (McKenedy, 2001).

"The basic concept then of biomass as a renewable energy resource comprises the capture of solar energy and carbon from ambient CO_2 in growing biomass, which is converted to other fuels (biofuels, synfuels) or is used directly as a source of thermal energy or hydrogen. One cycle is completed when the biomass or derived fuel is combusted. This is equivalent to releasing the captured solar energy and returning the carbon fixed during photosynthesis to the atmosphere as CO_2" (Donald, 1998).

These quotes are clearly showing that the burning of (just) grown biomass is balanced process in the sense of CO_2 emissions. And this would be possible to say it the other way around. If this theory is correct we can apply it to any fossil fuel as well. Therefore in consequences it would be theoretically possible to balance these emissions always with burning the "NEW biomass" (so-called by McKendry (2001)) instead to pollute our planet with easier reached and performed fossil fuels, especially for burning or distribution. The fact that biomass helps (doesn`t harm) to our planet is also proven by Demirbas et al. (2009). Biomass consumes the same amount of CO_2 during the growth as during the combustion, it is "neutral" source of energy *"… overall CO_2 emissions can be reduced because biomass is a CO_2 neutral fuel"*.

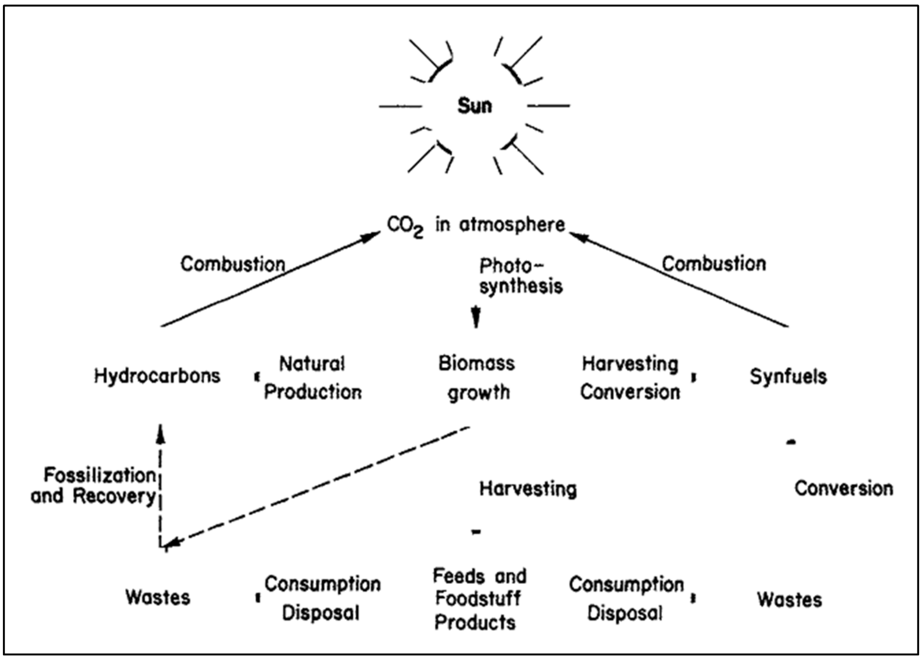

Figure 2.3: Main features of biomass energy technology (Source: Donald, 1998).

It is concluded that there are following relations. The carbon dioxide is being exuded by burning of biomass ether in “new” or “old” stage, meaning in burning biomass or fossil fuel, respectively. So the following scheme (Figure 2.3) is showing the cycle of biomass energy, the “new” stage regarding to McKendry (2001) citation. From the top part, through the Photosynthesis where there is an input of CO_2 and sun light and output the Oxygen used back in combustion to balance this natural cycle.

2.1.3 Drying biomass for commercial use

”With the prices of energy constantly rising, the use of biomass presents an option for decreasing energy dependency“ (Havrland et al., 2010). This fact seems positive for the biomass future; similar thoughts are mentioned in Demirbas et al. (2005). However, Bena and Fuller (2002) have opposite thoughts with compering solar dryer to other technologies: “..., solar dryers continue to struggle to gain acceptance by commercial producers”. Bena and Fuller (2002) says that only a small model of solar dryer was accepted due to its low cost and simple construction. For my opinion, the commercial farms may also see this high potential of combustion dryers, therefor, our question would be: Is it suitable to use solar dryers on the global scale for commercial farming to get ‘new’ energy?

Here might be correlation with the words of Bena and Fuller (2002) that the small scale solar dryers were only accepted through the market as mentioned above. To be able to use the biomass agricultural residues in commercial farming, there are two main steps to follow; (1) dry the selected biomass waste, (2) press the dried contend to the adequate form of briquettes (Havrland and Podebinschi, 2011). In this form the briquettes are available for direct combustion. The step (2) needs to be done according to the selected type of biomass waste / residues and also due to the type of boiler / back-up heater. There are additional steps to follow with an extra primary investment. Even thou it is necessary to concentrate for every step of drying process to eliminate the cost of the preparation phase. Theoretically, the primary cost and knowledge barrier are in this time still unsatisfied for the commercial farmers causing not much invests into this alternative energy field.

2.1.3.1 Circular Agricultural Model

Generally, the biomass combustion is for many people in agricultural a way to reuse their product – crop waste, for example, to gain an extra energy out of their wastes / residues. To follow the idea of '3R' (Reduction, Recycle and Reuse of wastes) towards the so-called 'Circular Agricultural Model' (Gangnibo et al., 2010). There should be a big potential to show a working models using the 3R models for other commercial farmers to increase the knowledge of advantages about biomass combustion process.

2.2 Biomass solar drying technologies

The types of solar dryers will be discussed to focus on estimation of the efficiency in the most used form of biomass solar energy. A definition of biomass solar energy is: „*The solar energy, which is stored in plants and animals or in the waste that they produce, is so-called biomass energy*"(Demirbas, 2005). Therefore the biomass energy is by the sun energy stored in the plant/tree.

Available literature shows diverse distribution over the solar drying techniques. There are many different classification groups of the dryers and the terminology is not always uniform over the diverse authors. However, there are common signs to classify them. Before the start with the overall classification it is necessary to exclude already mentioned traditional drying techniques such as open sun drying and drying by burning of fossil fuels or wood to be more concrete.

2.2.1 Generall classification of crop drying solar energy

The classification of anything is a natural way to generalize and understand more certain objectives, in general. In this case the generalization might seem simple but there are many dryers on the edge of one or another group a shown group below. Therefore it is more to make a picture of different general models of various drying techniques.

Now there are only the specified conventional dryers to classify. By Sharma et al. (2009) the convention drying technique is so-called "Controlled drying", see Figure 2.4.

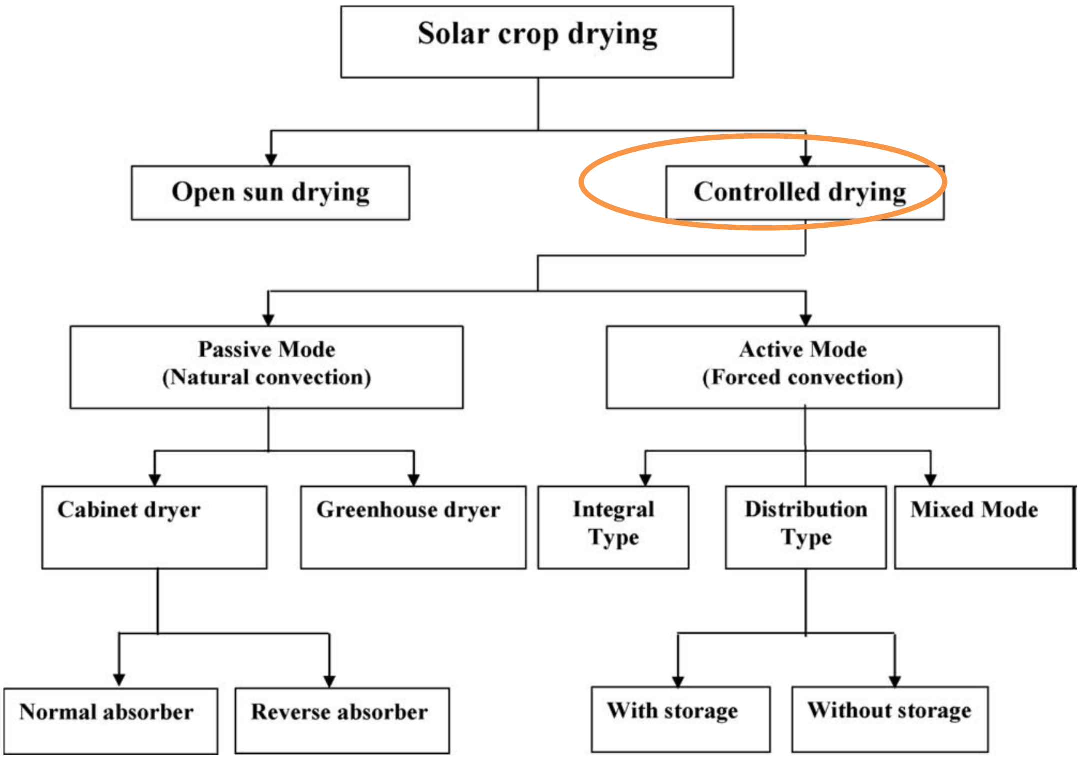

Figure 2.4: Classification of crop drying using solar energy (Source: Sharma et al. , 2009).

Solar dryers of controlled drying are classified into two main categories, generally: passive and active (Figure 2.4). The passive convention dryers are using the natural air flow of heated air only (typically with the entrance of the air lower than the outcome) and the forced convention dryer equipped with additional technologies such as. Amer et al. (2010) is using the terminology of non-forced and forced convention solar dryers. Forced dryers are designed to use an external source of energy to increase the drying efficiency, as one of the result of the Habilitation Thesis of Banout (2011).

Another dimension for the classification is the (a) direct, (b) indirect and (c) mixed drying technique. This classification is to get the classification from different perspective. In general the drying by (a) direct dryer is seen as more simple way due to the light coming through the plastic or glass cover (roof) straight down on the biomass stored in the drying chamber. On the other hand (b) indirect drying is more sophisticated by its separated sections of the helio-collector (in the case of direct drying the roof) and the drying chamber.

This is discussed by many authors, for example also by El-Sebaii and Shalaby (2011). Here the author is also taking in account another group of so-called (d) *"solar dryers with heat storage media"* where the additional boiler is present (Amer et al. 2010). The exchange of energy is taken in account to reach through the heat exchanger (in many case present after the reversible fan before the air enter the drying chamber) additional heat to decrease drying time, possibly during the off-shine hours.

Information of two dimension classification, compilation of (a), (b), (c) and (d) with the passive / active category is shown. The present matrix is to see the possible drying techniques derived by the previous classifications (see Table 2.2):

Table 2.2: Classification (compilation) of drying techniques (Source: own compilation according to Sharma et al. (2009), Amer et al. (2010) and VijayaVenkataRaman et al. (2012)).

Classification (category)	*Passive (non-forced) mode*	*Active (forced) mode*
(a) Direct solar *	Greenhouse *	Integral type
(b) Indirect solar *	Cabinet *	Distribution type
(c) Mixed *	Natural mixed model	Mixed model
(d) * with heat storage media	-	Back-up model

(* Dryer)

In the Table 2.2 there are all the possible types or models of solar dryer presented by El-Sebaii and Shalaby (2011) and Amer et al. (2010). The mentioned Back-up model is also presented by El-Sebaii and Shalaby (2011). For the passive mode the Dryers with the storage media heater were not found in practice due to its impropriety by already mentioned more simple construction design apart from the active mode. However, in contradiction for example VijayaVenkataRaman et al. (2012) is showing the Natural mixed mode dryer in more complex way used for example for drying cassava and other crops of so-called countries of global south. For the reason of practical part of the Thesis it would be suitable to mention the additional heat source dryers used in conventional active drying techniques.

2.2.2 Overlook of non-forced and forced convention solar dryers

As mentioned before, the solar dryers are generally possible to spread into two broad groups: non-forced and forced or passive and active. The non-forced (passive) dryers can be built easily, without any extra materials, reachable for small scale farmers. For example, raw construction materials such as wood may be used (Sharma et al., 2009).

2.2.2.1 Non-forced solar dryers

Non-forced dryers are used for the drying of biomass in smaller scale, in general. The passive drying is based on the chimney effect of the rising air flow or it is using the wind speed. There is another diversification of non-forced driers. It is the direct and indirect drying, where the direct drying is common for the passive drying system (Murthy, 2009). The non-forced direct dryer is shown in Figure 8.1 in Annex. This dryer is designed to directly absorb the solar energy, it is also called “greenhouse dryer” due to it similar look as the green house itself using the same heat income for different purpose. To come to the indirect form of drying system it is not usually found in practice that often. Therefore the mixed model of dryer is presented in the Figure 8.2. The mixed model is a combination of the direct and indirect drying where the dryer is basically designed as an indirect dryer with at least one or more walls made by a transparent material settled towards the potential sun radiation energy waves (El-Sebaii and Shalaby, 2011), see Figure 2.5 .

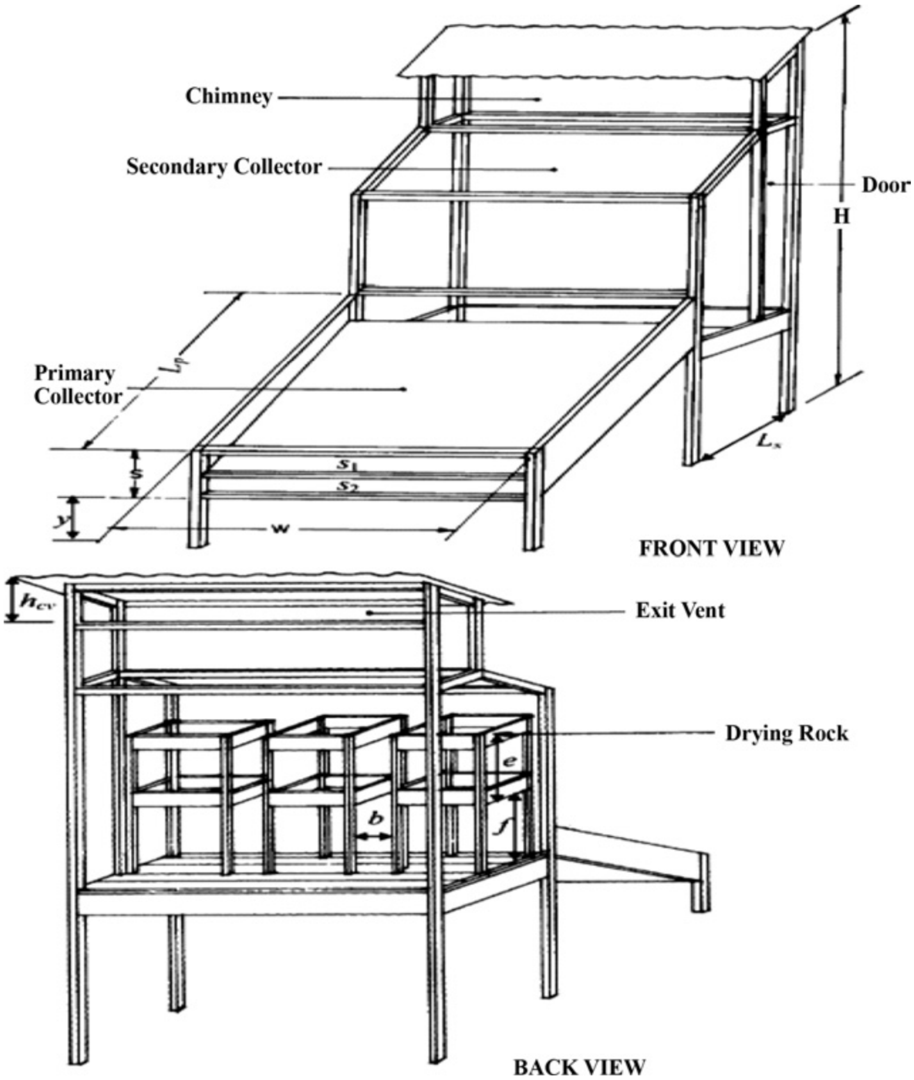

Figure 2.5: Schematic views of mix model non-forced dryer (Source: Forson el al., 2007))

The Figure 2.5 is showing an example of the passive mixed model (direct and indirect drying). In this case from the front view there is shown the so-called primary and secondary “solar collector” where the primary collector is playing the role of indirect drying (indirect heating up the inside air) and the secondary collector is playing an additional role with its direct sunlight to support the drying process. That is due to one wall with the same direction as the primary collector is transparent.

2.2.2.2 Forced solar dryers

In general, in the group of indirect dryers the active solar dryers are used more than the passive ones (Breundorter et al., 1985). But the construction is also more difficult, the following parts are included (for the active-indirect solar dyer), (see Figure 8.2 in Annex):

- Solar collector
- Pipe / mixing chamber
- Ventilator (with the additional heat exchanger – if added)
- Grate of the biomass layer
- Drying chamber

This solar dryer is designed with the additional heat source witch might be used for example in the off-shine hours. That is also the case of the practical work of this Thesis. Havrland and Pobedinschi (2011) are also showing the structure of the additional heating system (see Figure 2.6)

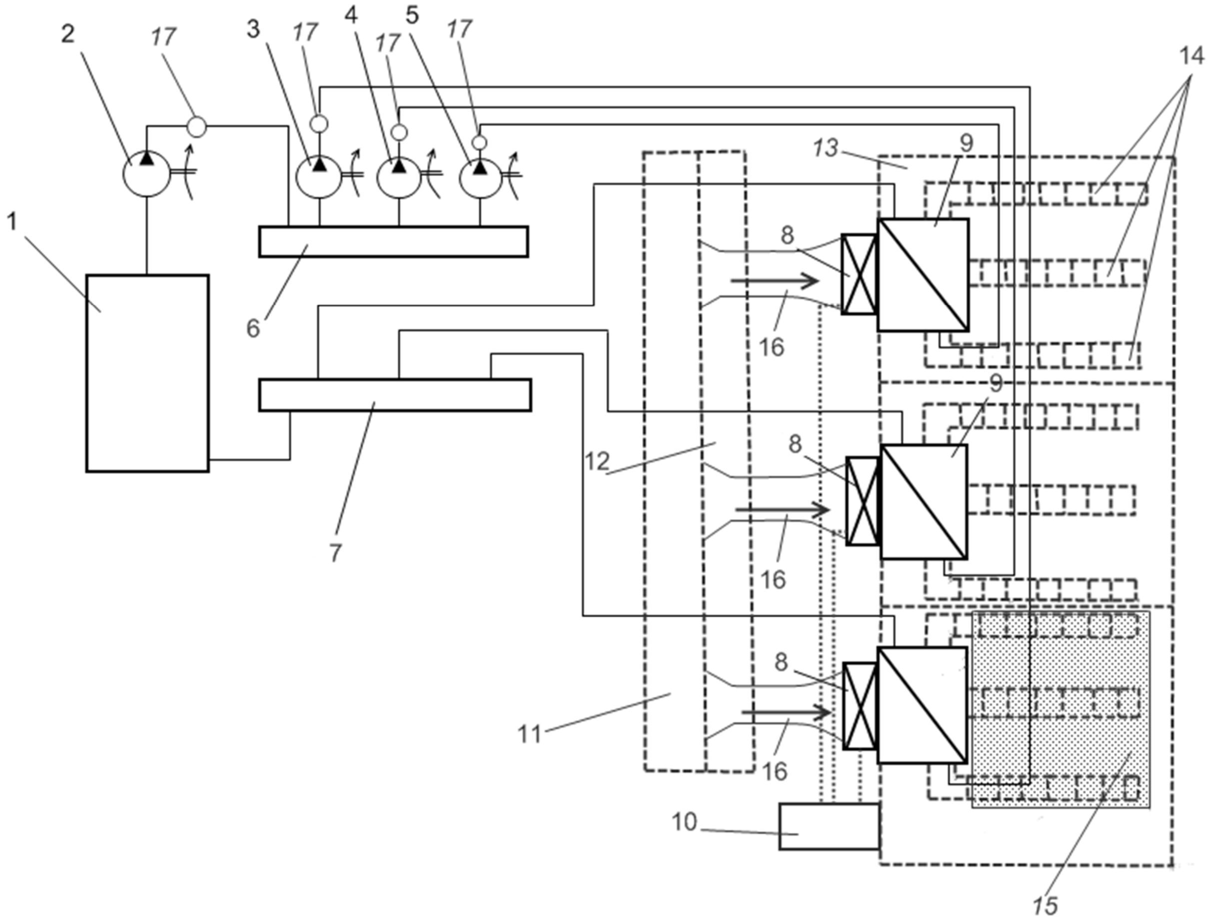

Figure 2.6: Scheme of the experimental combined dryer with the additional heat source

LEGENDE: 1 – boiler; 2-5 – pumps; 6,7 – distributors; 8 – reversible fan; 9 – heat exchanger; 10 – control panel; 11 – helio-collector; 13 – drying chamber; 14 – grid channels (grate); 15 – biomass layer; 16 – connection pipes; 17 – control devices

On the Figure 2.6 the scheme shows practical example of additional heat source. The simple way of the additional heater will be presented in this particular case working on the base of heat transfer by water medium. The boiler in this case for bio-briquet burning (Type: KTP 49) and is designed to heat up water in closed thermo-regulation system. The water is transferred by its pipes and pumps to the heat exchanger (Type: CIC H10). In the heater exchanger the heat energy from the water is transferred by the air to rise the air temperature for further drying process.

Forced dryers are designed to use an external source of energy to increase the drying efficiency, as one of the result of the Habilitation Thesis of Banout (2011). The idea of the forced dryers is to increase the speed of air flow inside the dryer. In different words the same idea is supported by following. "… higher flow rates [of air] increases the overall drying performance and efficiency" (VijayaVenkataRaman et al., 2012).

2.2.3 Overlook on types of helio-collectors

The air flow in relation with the speed rate is mentioned at the end of the previous chapter. This factor is besides other settlement and designs connected to the type of helio-collector used in particular solar dryer. There are different classifications over the available literature. However, the classifications suitable of the selected dryers will be discussed. The roofs for direct drying will be excluded due to its more simple design; the transparent cover material and the inclination are the factors to consider. In simple way the following (general) aspects are important to consider: area of the dryer, cover material, inclination slope, latitude and climate, use of the dryer, heat isolation.

The indirect drying is more complicated structure present. Therefore the importance of the helio-collector type is important. However, it is still important to keep in mind the general aspects of the collector.

The solar flat collector (Figure 4.5) and more advanced tubular collector is presented (Havrland and Podebinschi, 2011). The principle of tubular collector is to minimalize the heat looses by izolating the heated inseed tubber by vakuum. The annual efficiency of absorbtion is 20 – 30 % higher but have the price of that is several times higher as well. Therfore tubular collector is not suitable for practical use by my oppinion.

Other possible presented helio-collectors are by Murthy (2009) and VijayaVenkataRaman et al. (2012) as follows. The V-grove absorber used in Figure 2.7 is designed to absorbe extra heat, that is on the other hand shifted to its more sofisticated and more expensive luxury.

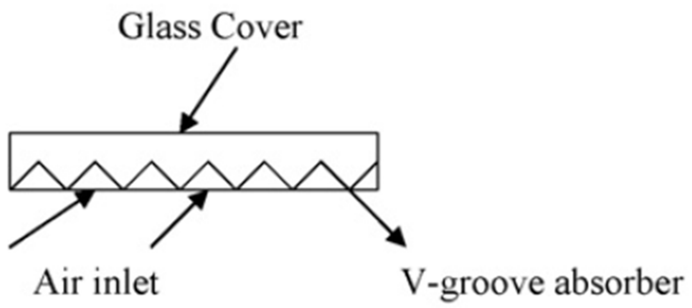

Figure 2.7: V-Groove absorber design

Another presented collector is so-called double pass using a semi-pass material to increase the outcome temperature of the helio-collector medium Figure 2.8. This design of the double-pass collector is also used in particular dryer presented by Banout et al. (2011) for drying suitable to smaller amount of more valuable agicultural product.

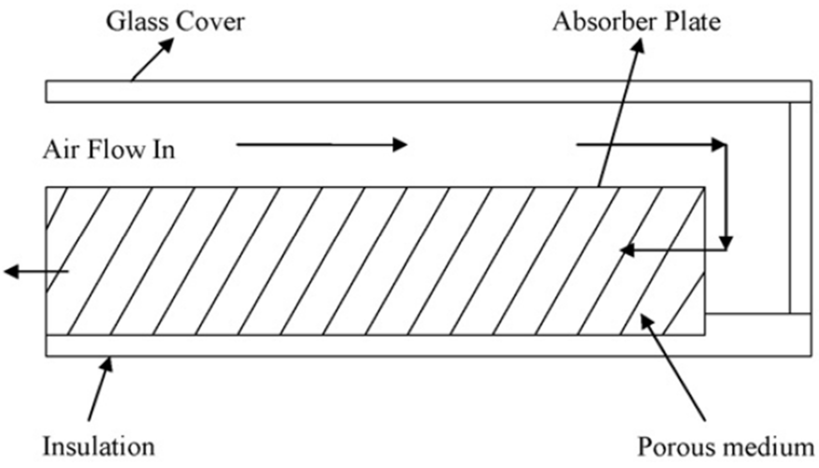

Figure 2.8: Double-pass solar collector

3. Aims of the Thesis

3.1 Objectives

The main objective of the Thesis is to analyse the drying processes of selected biomass in the experimental solar dryer build in Moldova. Survey is based on previous research in the similar conditions with the comparable methodology. The analyses of drying processes may conclude the possible use of the dryer to advice new ideas of drying techniques.

In order to fulfil the main objective the following sub-objectives are selected:

1. To collect the biomass for use as energy plant followed by preparation of the material for drying process – topinambour (*Helianthus tuberosus l.*).

2. Survey the changes of biomass moisture in the in different places of the biomass layer during the whole drying process.

3. Measurements and analysis the main drying parameters such as relative air humidity, temperature and speed of air flow in different selected points located inside all parts of the experimental dryer.

4. Compare the drying process of wooden and crop biomass, with the use of the previous results.

5. Propose and recommend new ideas for improvement of drying process and the design on the dryer based on the results gained from the practical measurements and actual experience.

3.2 Research Questions

There are several aims to be done in this work besides to provide the information to support the biomass drying technology in general.

1. Compile the knowledge on biomass drying process and elaborate the theoretical fundamentals to gain sufficient information about the drying process in brother range.
2. Measure the drying factors of solar dryer with more frequent outcomes and compare measured results with the other experiments with selected biomass and their pre-drying processing.
3. Discuss the results and present conclusions for future research with consideration of new pre-done analyses before.

4. Methodology

The Thesis was done during the selected phase of over one year 10/2012 – 03/2014. The preparation phase was based on the literature research and theoretical work assignment. Before the actual survey of biomass drying there was already some research done. Practical field work was performed during the September 2013. Measurements and calculations where obtained during this phase. After the survey the final steps of theoretical considerations were done and the work was focused on the results and discussion.

Methodology of the assignment was strongly inspirated by Havrland and Podebinschi (pp. 7-21). Measurements were taken in same place and season time under the similar conditions.

4.1 Conditions and location of the practical field work

Practical field work was done during the September 2013 (from 2nd until 15th) in Republic of Moldova Chisinau. The experimental solar dryer is located in the State Agrarian University of Moldova. The climate characteristics of the region (see Figure 4.1) are shown in the Table 4.1.

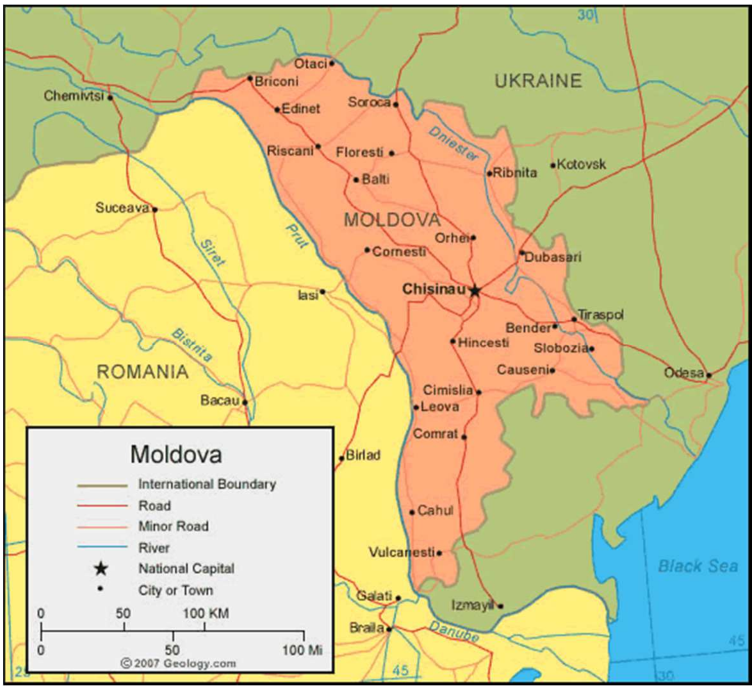

Figure 4.1: Political map, Republic of Moldova

Table 4.1: Climate characteristics for Chisinau, Moldova (source: Aquastat – FAO, 2013)

Latitude: 47.054° Longitude: 28.852° Elevation: 101m

Month	(A) Tmp. Mean °C	(B) Tmp. max. °C	(C) Tmp. min. °C	(D) Grnd Frost days	(E) Rel. hum. %	(F) Sun shine %	(G) Wind (2m) m/s
Jan	-2.9	0.2	-6	26.5	86.3	27.3	2.6
Feb	-1.3	1.7	-4.3	22.7	84.8	27.9	2.7
Mar	3.5	7.3	-0.3	18.1	76.6	34.6	2.7
Apr	10.9	15.9	5.9	4.7	64.5	46	2.7
May	16.7	22	11.5	0	62.3	54.7	2.5
Jun	20	25.3	14.8	0	63.7	59.9	2.4
Jul	21.5	26.7	16.3	0	64.2	62.7	2.3
Aug	21.1	26.6	15.7	0	62.4	67.1	2.4
Sep	**17**	**22.4**	**11.6**	**0**	**65.2**	**60.5**	**1.9**
Oct	10.9	15.6	6.2	4.7	72.9	51.2	2
Nov	4.9	8.2	1.7	13.4	83.3	26.4	2.5
Dec	0.1	2.9	-2.7	22.4	86.3	22.8	2.6

Legende: (A) Mean temperature in °C,(B) Maximum temperature in °C,(C) Minimum temperature in °C,(D) Days of groundfrost,(E) Relative humidity in percentage,(F) Sunshine fraction in percentage, (G) wind speed

The overall process was divided into three main phases (the following dates are in September):

1. Collection of the organic material (1 day, on 2nd);
2. Preparation phase for the drying process of the collected material (1 day, on 3th);
3. Survey of the collected material as the longest phase of the process in this particular phase of the drying process. This step was divided into two main phases. The first phase (a) was done under the same conditions of the measurements (9 days, from 4th to 12th). The second phase (b) was decided to obtain due to uneven distribution of the moisture content to complete the drying process (3 days, from 13th to 15th). Each day (before the first measuring) of the second phase the material was mixed due its uneven moisture content at the end of the first phase.

4.2 Material used for the drying process

The sellected plant suitable for the drying process and further energy use was *Helianthus tuberosus l.* (Topinambour) spp. *Asteraceae* also known as Topinambour or Jerusalem artichoke see Figure 4.2. The plant is originated from the eastern North America with its rough leaves and yellow flowers growing up to 3m of height. It is cultivated for its tuber, which is used as a root vegetable. Besides that *Helianthus tuberosus l.* is known as an energy plant.

Figure 4.2: Topinambour before harvesting (foto: author)

Figure 4.3: Harvesting of the sellected biomass (foto: author)

A broad specification for an **energy crop** is a crop grown for energy application. In this case the energy application would be possibly used after drying in a form of bio-briquettes for burning.

The material was collected (1^{st} phase) during the DAY 1 of the experiment. It was done manually in the Botanical Garden of Chisinau. The fresh biomass was first harvested (a) and packed into bunches, stored (b) on the transporting track and then transported (c) to the university campus, see Figure 4.3.

The Figure 4.2 shows the preparation phase; there the material was crushed with an automatic stationary crusher run by its own engine.

Figure 4.2: Preparation phase of biomass (foto: author)

Figure 4.3: Prepared material stored in the drying chamber (foto: author)

The material was crushed into small pieces with an approximate wide of 1-2 cm. The initial height of the stored material (layer) in the drying chamber was about 25 cm, see Figure 4.3.

In the drying chamber after the preparation phase the **initial moisture content** of the material stored was measured to be **75.5 %**.

4.3 Specification of the experimental solar dryer

The following part is focused on the technical drying ability of the experimental biomass dryer. It is showing the technical parameters (of construction) and its functional mechanisms (working process). Equipment and construction of the solar dryer (see Figure 4.4) was projected by team of specialist from Czech University of Life Sciences Prague and Research Institute of Agriculture Engineering Prague in cooperation with research workers from State Agrarian University of Moldova Chisinau (Havrland and Podebinschi, 2011).

Figure 4.4: Front view of experimental solar dryer (foto: author)

4.3.1 Construction of the biomass dryer

The solar dryer has these main parts as the wind flows respectively: (a) helio-collector warms the air floating to (b) mixing chamber for the mixing of air before the intake by fans to (c) drying chamber were the air runs into the biomass layer.

Characteristics of the (a) helio-collector and (c) drying chamber

The drying chamber of the present dryer is a three section “garage” designed for a two wheel vehicle to in case of need enter (for example to unload the material) the inside of the chamber without passing (deforming) the drying channels. The total ground-area of each of drying chamber is 24 m^2 of six times four meters (see Figure 4.5). The drying chamber is equipped with the three channels as a root for the wind blow covered by ion solid grids with possible lift up for the maintenance purposes.

The roof of the solar dryer is designed as a one-layer transparent cover made by polycarbonate panels to minimalize the heat losses of the helio-collector and its absorber by irradiation out of the system. The light transitivity should be below one, about 0.8 or lower (by its appearance of dirt) for the short and medium waves (300 - 600 nm) (Ivanova, 2012). The distance between the polycarbonate cover and the absorber (channel bottom) is 15 cm high. The roof is separated into three parts as the dryer has three sections and the total helio-collector is 87.5 m^2.

The geographical orientation is south-eastern, there is deviation from the optimum of 30 degrees angel, this leads to some loses, reduction of the captured energy is about 5 % (Ivanova, 2012), see Figure 4.5.

Figure 4.5: Detail of the roof, helio-collector - left; Drying chambre - right (foto: author)

4.3.2 The principle of working process of biomass dryer

The convention principle of drying is present in this specific biomass dryer. The convention principle is based on the evaporation of the water liquid present in biomass to spread in by the air flow into the air. The initially heated air is conveyed by the fan into the drying chamber to the process of heat and mass exchange causing the drying of material.

The simple scheme principle of drying is shown in the Figure 4.6.

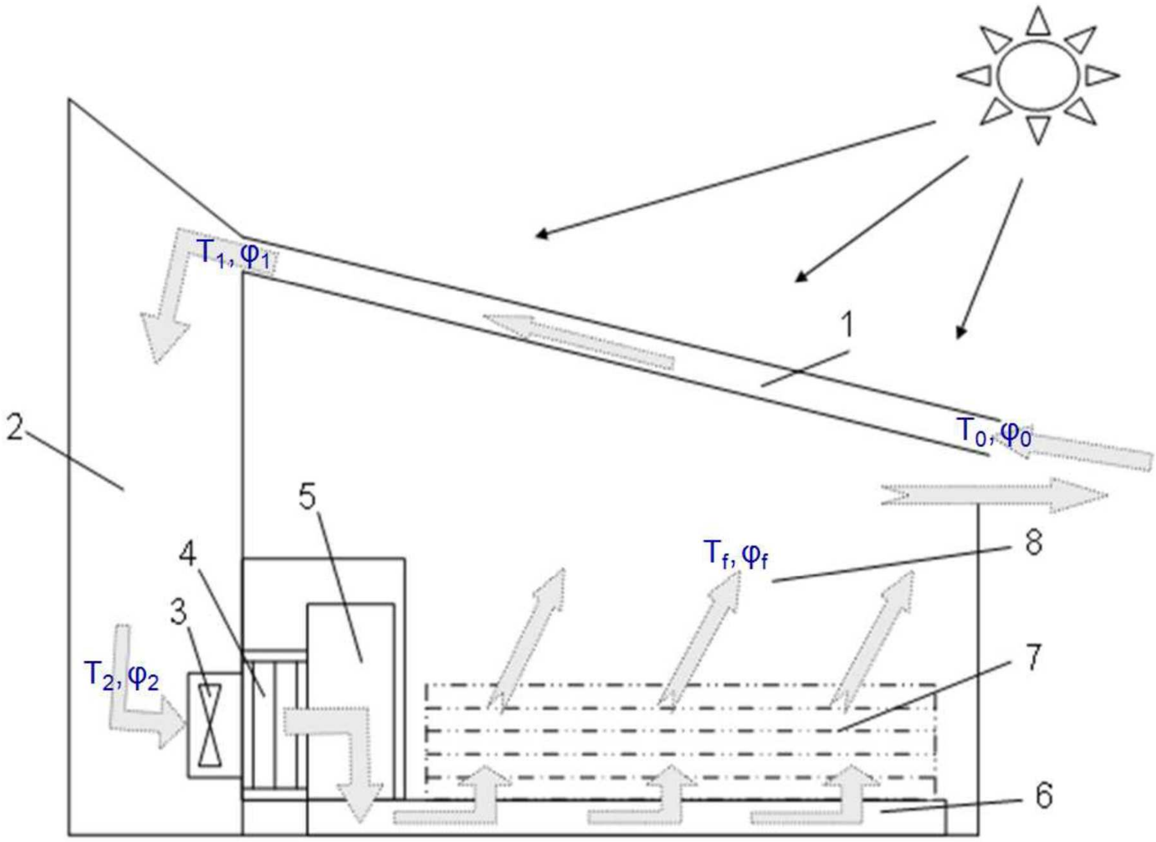

Figure 4.6: Demonstration of air flow directions, side view of the biomass dryer (source: Ivanova, 2012)

Legende: 1 – helio-collector, 2 – mixing chamber, 3 – fan, 4 – heat exchanger, 5 – air distributer in side directions of front view, 6 – three parallel flor channels, 7 – biomass layer, 8 – drying chamber; T – temperature, φ - air humidity shown in diferent phases of the overall drying process; the T and φ for 0, 1, 2, f are showing some measurement point of the air parameters.

The Figure 4.6 refers to following cycles: The air from outside enters the (1) helio-collector due to the lower pressure of (2) mixing chamber made by the (3) reverse fans. Each of the fan forces the heated air through the (4) air exchanger and (5) distributor further through the (6) channels finally towards the (7) biomass layer which penetrates the material and exchange the moisture to humidity ended in the (8) drying chamber and left out of the system outside with added humidity content.

4.4 Measurement techniques for survey of the main drying parameters

During the drying process there were two separated measuring processes done simultaneously during the first nine days (from 4^{th} to 12^{th} September). After this phase the material was mixed, to eliminate uneven moisture of non-dried layers or sections, during the period of three days (from 13^{th} to 15^{th} September).

Therefor it is necessary to explain these two measuring processes separately; the moisture content measurement (see chapter 5.4.1) and the measurement of air temperature, relative humidity and air flow (see chapter 5.4.2).

4.4.1 The moisture content measurement

After the measured initial moisture content of the stored material on the 4^{th} September the measuring phase started with measurements of moisture content three times a day (M – morning, N – noon, A – afternoon) in six different places (L1 – L6) of the drying chamber to monitor the distribution of the moisture during the selected days.

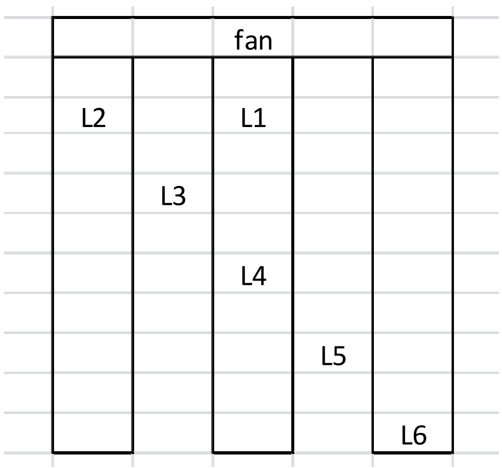

Figure 4.7: Distribution of points L1 - 6 for measuring the moisture content

The Figure 4.7 shows the places where the samples where obtained during the measuring days. The samples were collected always from the about 10 cm under the surface and collected into separated bowls for further elaboration.

Determination of moisture content of the samples

After the selection and labeling of samples the moisture elaboration was done according to ČSN P CEN/TS 14774-1 (-2, -3) by using the oven drying method. The oven MEMMERT model 100-800 (Schwabach, Germany) was used with volume up to 100 dm^3 and programmable timer, see the equipment Figure 4.8.

Figure 4.8: Equipment for determination of moisture content (foto: author)

The determination process was done by following step:

- The samples of material (L1 – L6) where collected and placed in bowls of already known weight and weighted with the collected material – mw (g)
    - KERN EW 3000 - 2M or DENVER INSTRUMENT MXX-2001 with preciseness up to 0.01 g was used to measure the weight before and after oven drying
- All the samples were placed in the oven and dried for 8 hours at 105 °C
- After the drying process the samples were taken and weight again to obtain the dry matter – md (g)
- By the following simple formula the material moisture content was calculated – w (%):
    - w (%) = [(mw - md) / mw] . 100

4.4.2 The measurement of air temperature, humidity and air flow

The other part of the survey on drying process was done by the measurement of temperature and humidity nine times a day from 9 am to 6 pm during seven days from 4th to 10th of September.

The Figure 4.9 is mapping the positions of different places for measuring the mentioned parameters (temperature, humidity and partly velocity) explained separately in following text.

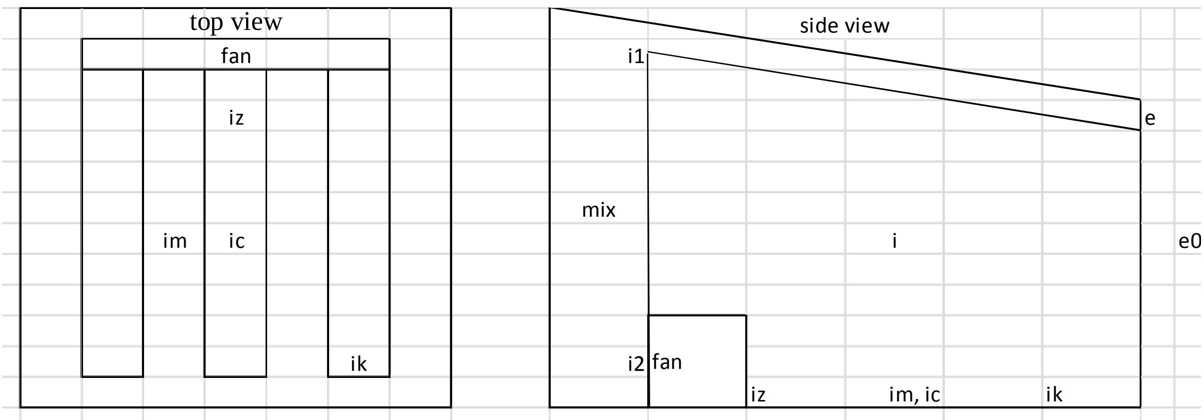

Figure 4.9: Top and side view for measuring the temperature, humidity, (air flow) in and out of the drying chamber

Legende: e0 – ouside, e – by the entrance of the helio-collector, i1 – by the entrance of mixing chamber, mix – in the mixing chamber, i2 – before the fan intake, iz – clouse to the fan in biomass layer, im – between the chanels in biomass layer, ic – above the channel in biomass layer, ik – by the end of channel in biomass layer, i – in the drying chamber above the biomass layer.

Figure 4.10: Equipment for the data measured (foto: author)

Legende: A – measuring of humidity or temperature in inside the biomass layer, B – fan in mixing chamber – measuring, C – measurment equipment: LUTRON LM81HT and LM81AM, D – mixing chamber

The temperature was measured by LUTRON LM81HT "Humidity/Temperature Meter" with resolution of 0.1 °C in range of 0 – 50 °C. at all the places shown in the Figure 4.10. The position of the measurements drawn in biomass ($T_{iz,\ im,\ ic,\ ik}$) was done approximately 10 cm from the surface inside biomass layer.

The humidity was measured also by LUTRON LM81HT "Humidity/Temperature Meter" with resolution of 0.1 % RM (relative humidity) in range of 10 – 95 % RM. The position of the measurements drawn in biomass ($\rho_{iz,\ im,\ ic,\ ik}$) was done approximately 10 cm from the surface inside biomass layer.

The air flow was measured by LUTRON LM81AM "Anemometer" with resolution of 0.1 m/s in range of 0.4 – 30.0 m/s only at selected places ($V_{e,\ i1,\ i2,\ iz,\ ic,\ ik}$) due to its constant air flow. The measurements of air flow were collected only three times a day and for my opinion are not much precise due to its disability of the selected Anemometer to measure low speed of air flow.

5. Results and Discussions

Through the survey process many measuring steps were done to show the results of efficiency and ability of the experimental solar dryer. The gained data were collected in the same conditions and under the similar methodology as the previous Ph.D. Thesis of Ivanova (2012).

The differences to gain comparable results are pointed out:

- The material of experiment differs by its initial moisture due to different energy crop selected.
- The measurements were done more times a day to gain more precise results.
- The average temperature of this experiment was lower than in 2012, however, this might be also seen as a possibility to determinate the suitable weather conditions.

However, due to more factors which differs from the previous mentioned experiment (especially the weather conditions) we can in many issues only assume the connections, but cannot make the reliable conclusions. But to compare the result in general scale the specific present dryer should not be generalized, the selected results appear to be specific.

General parameters of drying process

The collection of data was done according to the mentioned methodology from the 4th of September to 12th of September and after that for another three days up to 15th of September to gain extra results; done in the experimental dryer at the State Agrarian University, Chisinau. The prepared Topinambour was filled in the drying chamber to survey the drying process. All the days of the experiment the fans AVEN 630H/500E were working from 9 a.m. to 6 p.m.

Therefore there are two types of data analysed. The first is the moisture content elaborated within the variety places in the biomass layer measured (see chapter 6.1.). The second separated measurements were done with the humidity, temperature and air flow (see chapter 6.2.) shown as the crucial parameters for survey on biomass drying process.

5.1 *Analysis of Drying Process according to moisture content*

The measurements of moisture content were done during the first 10 days with using the same methodology as shown in Biomass Processing to Biofuels (2011), three times a day at 9 a.m., 1 p.m. and 5 p.m. each time at six different place (L1, L2, …, L6), see in methodology chapter 5.1.

Analysis of the first phase (from 1st to 10th day)

From the results (see Figure 5.1) it is seen that the moisture content decreases above the channels (L1, L2, L4, L6) in few days. However, there is almost no change in the case of the measured points between the channels, see L3 and L5. Roughly speaking, the moisture content of these "in-between areas" is not working appropriately, and theoretically only some amount of material is being dried.

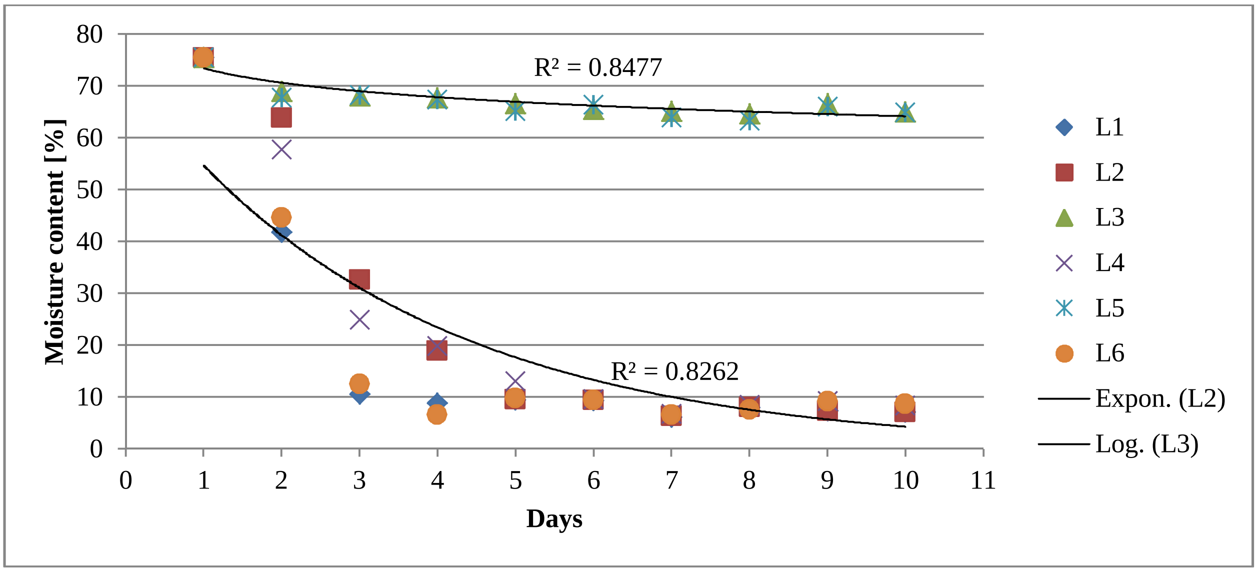

Figure 5.1: Average moisture content for the first phase (from 1st to 10th day), for L1 - L6

The mentioned moisture content above the channels (L1, L2, L4, L6) is possible spread into two time sections. In the days 1st to 5th is seen constant rapid moisture a humidity decreasing below the 15 % of moisture content to usable for further briquetting for example. In the second section (6th to 10th day) is already almost not showing any noticeable changes and the material is already at its dried level. In comparison to the points between the channels (L3, L5), the similar trend of no significant changes occurs in for the whole cycles of the first ten days (see also Figure 5.3).

In the Annex form the Figure 8.5 it is showing the profile of moisture content developing during the time at the points of L2 – L6 as each point shows front-view horizontal position of the layer profile (different color present different moisture content). This model is not counting the differences of the distance from the fan (back side of the drying chamber), for example, the moisture content of L2 is seen in the same data line (date) as the L6 and the other way around.

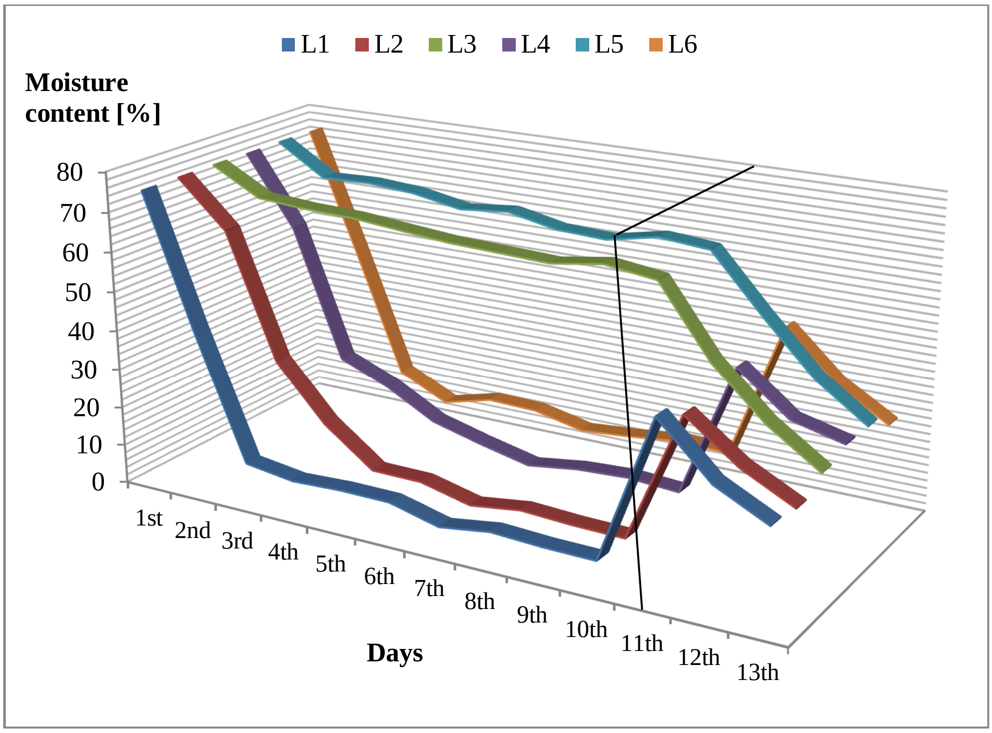

Figure 5.2: Moisture content from 1st to 13th day at the places L1 – 6.

Analysis of the second phase (from 11th to 13th day) with comparison with the first phase

Before the 11th day, the material was mixed, the same was done always the 12th and 13th to include the other proposed technique. It is seen that the mixing of the biomass has positive effect to the homogeny of the material from the moisture point of view. The other possible result would be that there is not difference of the total moisture of the material. But from the 5th to 10th day we already see no more significant differences. In the Figure 5.2 it is seen that only the measured points L3 and L5 stay at the high moisture content for all the drying days, the Figure 5.3 is therefore showing already separated average of these two groups of different drying trends. From this it is strongly showing the stagnation phase from the days 6th to 10th as written in the part Analysis of the first phase. Therefore it is possible to say that from the 6th to 10th day the drying was not found useful at all. Material between the channels was already dried enough, but the material between the channels was not dry at all. Now it would be interesting to see know what is the distribution of the wet (between the channels) and (above the channels) dry material before the 11th day.

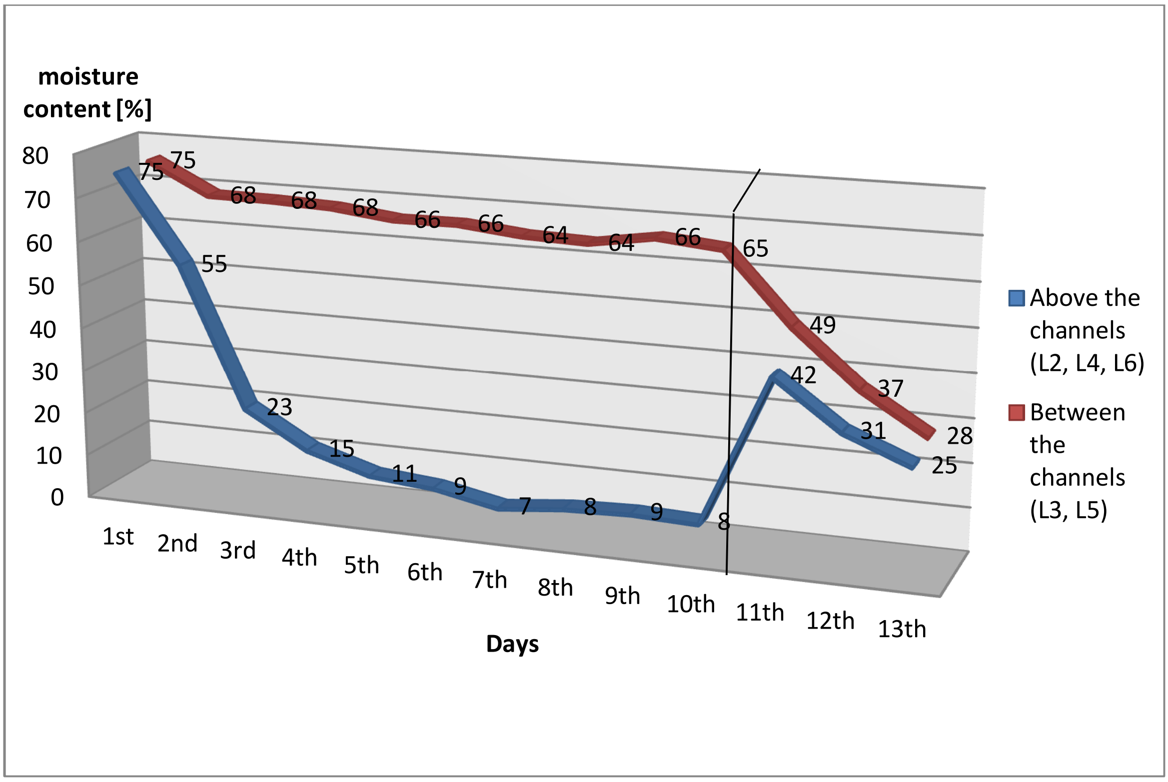

Figure 5.3: Difference of the moisture above the channels and between the channels in time.

The results were influenced by the mixing of content and from the initial (before mixing) and final (after mixing) average percentage of these two groups (see 10th and 11th day) of the results, it is possible to assume the proportional distribution (see Table 5.1).

Table 5.1: Average moisture content for determination of wet and dry distribution

	Morning 10th day		Morning 11th day
	L2, L4, L5	L3, L5	L1-6
L2	9.6		48.5
L3		66.0	49.8
L4	10.6		49.4
L5		65.3	53.1
L6	10.8		51.7
Average	10.3	65.7	50.5

Calculation of the theoretical distribution of the material:

$$10.3x + 65.7y = 50.5(x + y)$$

$$10.3x + 65.7y = 50.5x + 50.5y$$

$$(10.3 - 50.5)x + (65.7 - 50.5)y = 0$$

$$13.6y = 40.2x$$

$$\frac{15.2}{40.2} = \frac{x}{y}$$

The ratio of the distribution of material originated from the above (x; L2, L4 and L6) and between (y; L3, L5) is 1:2.64 (27 % and 73%, respectively). This ratio of approx. 2:5 is the theoretical ratio of the dry material (moisture about 10 %) and the wet material (moisture about 66 %), respectively at the 10th to 11th day. Both of the data are used from the morning measurements, first the 10th to get the material before mixing (with assumption of stagnation second phase, see part Analysis of first phase – 6th to 10th day) and secondly to compare it with the average moisture content after the mixing from the morning of 11th day.

The trend is similar to the assumption of previous experiments of the examination of this solar dryer. Even thou, in dissertation Thesis of Ivanova (2012), the differences of the between and above channels moisture is not that significant. It is probably due to its slightly divers initial conditions present and the material used. However, the (negative) exponential trend of the drying biomass in the first stage seems to have common sights of the lowering moisture content. This fact proofs the ability of dryer to represent the indirect drying of active type dryer with high efficiency.

5.2 Analysis of Drying Process according to relative air humidity and temperature, air flow

After the harvesting and preparation phase from the 2nd up to 8th day the relative air temperature T (°C) and air humidity φ (%) were measured 9 times a day from 9 a.m. to 6 p.m. daily at 10 places (see Figure 4.6 in chapter 4.3.2). The points were selected for to survey the process of the drying with the use of the same methodology as used in dissertation Thesis of Ivanova (2012). The air flow is also a part of the chapter with results showing the collected data from the same days measured only three times a day. These climatic conditions (Figure 4.1) were very similar to the moisture content.

In comparison of the already analyzed process of relative humidity and temperature, the results are showing the similar trend. It is interesting to see that the results of Ivanova (2012) is also proving high drop of temperature in the mixing chamber.

Air temperature survey in selected places

The temperature of the following points was measured to see the heat flow. From the Figure 5.4, it is evident that the highest temperature is at the entrance to the mixing chamber (points T_{i1}, the solid line) where the temperature is at its peak around 1 p.m. (13h) and after that is again slowly changing. The outside temperature (points T_{e0}, dots line) is following the trend of the temperature of the heated air and the gained temperature is shown by the red arrow (at 1 p.m.). However, the high temperature of the T_{i1} radically drops (see blue arrow).

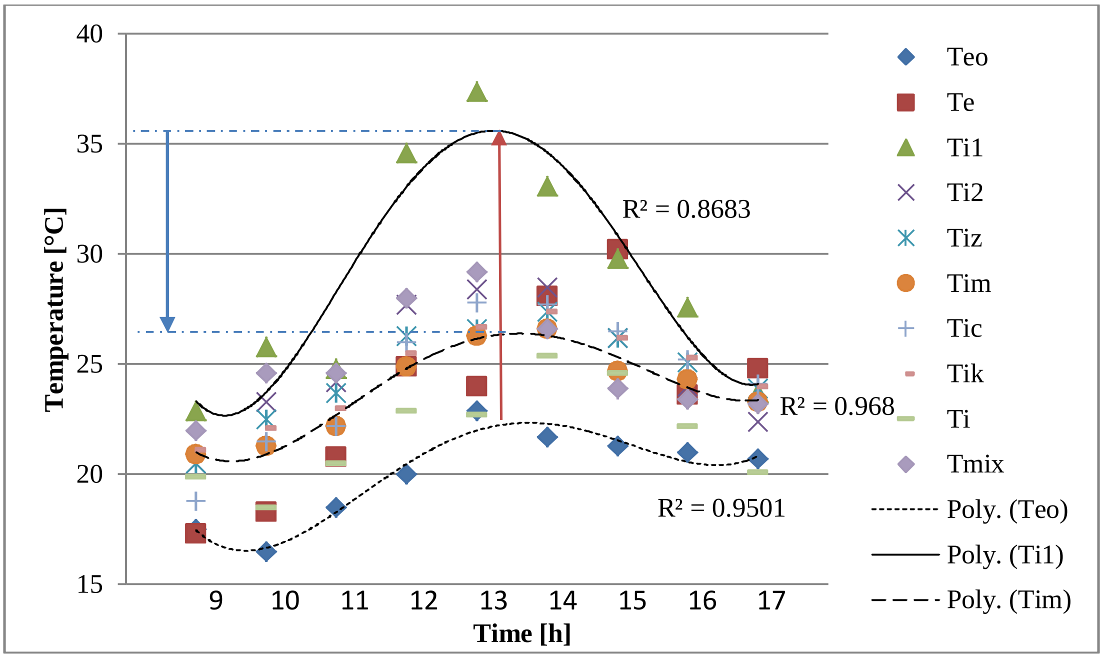

Figure 5.4: Temperature of the selected (4th) day measured

Legede: T_{e0} – ouside air temperature, T_e – temeperature by the entrance of the helio-collector, T_{i1} – temperatue by the entrance of mixing chamber, T_{i2} – temperature before the fan intake, T_{iz} – Temperature by the fan in biomass layer, T_{im} – temperature between the chanels in biomass layer, T_{ic} – temperature above the channel in biomass layer, T_{ik} – temperature by the end of channel in biomass layer, T_i – temperature in the drying chamber above the biomass layer, T_{mix} – temperature inside the mixing chamber.

During the midday, around 1 p.m. the temperature is showing gain of up to 15 °C (red arrow) as a difference of the income and outcome of the heli-collector, but the drop inside of the mixing chamber is about 8 °C (blue arrow). Similar trend is during seen during the whole day. For example in the morning (10 a.m.) and the afternoon (4 p.m.) the gain is about 6 °C and the drop is showing around 2.5 °C. From these data it is possible to say that the transfer of the energy through the mixing chamber is highly wasteful, from the energy point of view.

Air humidity survey in selected places

From the Figure 5.5 of the relative air humidity, it is evident that the highest humidity occuses in the biomass layer occures between the channels (see Figure 5.5) at point φ_{im}.

With the comparison of φ_{ic} (above the channel) there is a huge difference also comperable to the results of moisture content (from the Chapter 5.1).

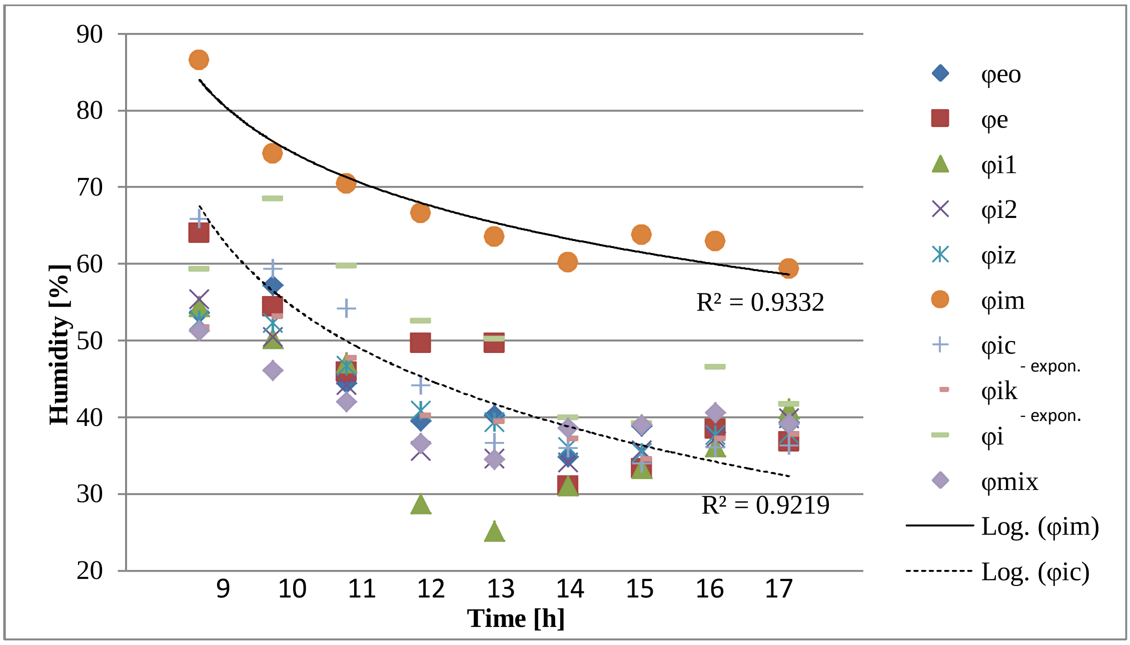

Figure 5.5: Air humidity of the selected (4th) day measured

Legede: Φ_{e0} – ouside air humidity, Φ_e – humidity by the entrance of the helio-collector, Φ_{i1} – temperatue by the entrance of mixing chamber, Φ_{i2} – humidity before the fan intake, Φ_{iz} – humidity by the fan in biomass layer, Φ_{im} – humidity between the chanels in biomass layer, Φ_{ic} – humidity above the channel in biomass layer, Φ_{ik} – humidity by the end of channel in biomass layer, Φ_i – humidity in the drying chamber above the biomass layer, Φ_{mix} – humidity inside the mixing chamber.

Air flow survey in selected places

The air flow measurements were to only gain the overlook of the air speed for different sections of the solar dryer. However, from the result it is seen that the places of air flow lower than 0.4 m/s are no representative due to this minimum possible level of air flow speed to measure (see Chapter 4.4.2 – The air flow).

Table 5.2: Air flow [m/s]

day	Ve	Vi1	Vi2	Viz	Vic	Vik
2nd	0.6	0.4	4.8	0.9	0.2	0.2
3th	0.2	0.5	4.7	1.6	0.4	0.1
4th	0.0	0.7	4.5	1.0	0.3	0.2
5th	0.0	0.5	4.9	0.6	0.2	0.2
6th	0.0	0.4	4.6	0.9	0.2	0.1
7th	0.0	0.6	5.4	0.9	0.1	0.1
8th	0.1	0.2	5.0	0.5	0.2	0.2
Average	**~~0.1~~**	**0.5**	**4.8**	**0.9**	**~~0.2~~**	**~~0.1~~**
Result	**Below 0.4**	**0.5**	**4.8**	**0.9**	**Below 0.4**	**Below 0.4**

Legende: V_e – by the entrance of the helio-collector, V_{i1} – by the entrance of mixing chamber, V_{mix} – in the mixing chamber, V_{i2} – before the fan intake, V_{iz} – clouse by the fan in biomass layer, V_{ic} – above the channel in biomass layer, V_{ik} – by the end of channel in biomass layer.

The last line of the Table 5.2 is showing average measured air flow during the selected time with the consideration of the measuring equipment. The average speed of reverse fan (V_{i2}) is 4.8 ms^{-1} and the average speed close by the fan in biomass layer is 0.9 ms^{-1}. This speed decrease is probably caused by the wider area of the space for the air flow as the same volume of air is transferred. The same terminology would be used in the case of speed by the entrance of mixing chamber (V_{i1}). On the edge of the drying chamber, the speed of air flow seems to be lower than close to the fan.

From other data we cannot see the trend of differences and the only gained data are following: (a) the measured air speed might be important for further calculations of efficiency of drying process and (b) equipment for measuring should be designed to be possible to also measure the lower speed of air flow.

6. Conclusions and Recommendations

The experiment on the survey on solar dryer efficiency was running during the September 2013 for 13 days in total, in Republic of Moldova Chisinau. The climate characteristics of the region are suitable for the case of solar technology but the weather was at the lower temperature than average.

6.1 Conclusions

Several conclusions of theoretical part were collected:

- The broad potential of solar drying should be used also due to the fact that from the traditional drying techniques it is four times more efficient from the time and energy perspective.
- Burning of biomass is a balanced process from the natural perspective (for example CO_2 emissions).
- The more sophisticated (with higher air flow), the more efficient the dryer is. There are different types of dryers suitable to different load, material and climate conditions.

From the practical field measurements the following conclusions are drawn:

- Due to big heat losses inside of the mixing chamber, energy transfer in this section should be upgraded.
- The experimental dryer is not designed to dry the biomass equally in all the places due to its low area of grid over the total drying area (in the drying chamber).
- Mixing of the material (in the second stage, 11^{th} – 13^{th} day) proved to be suitable for drying the biomass equally. This would suppress so-called "death zone" inside the drying chamber.

6.2 Recommendations

The attractiveness of biomass use for the combustion should rise by the use of more efficient ways of drying. That is also corresponding with an idea to shift the natural environment up to higher respect with depression of fossil fuel consumption.

The moisture results are supporting the fact of the uneven drying ability over the drying chamber. Supported by the theoretical results from the discussion we may prove that different type and structure of drying material is specifically more or less suitable for the selected dryer. Therefor the dryer is designed for specific structure and type (size) of material (wider than 1-2 cm). Theoretically the dryer is, due to its drying channels far from each other, design for less homogeny structure to distribute air possibly over the all corners of biomass layer.

Here are the notes for further measurements (not only applicable for the experimental dryer):

- To install isolated pipe connection between the outcomes of the helio-collector and income to the reverse fan.

- From the results of after mixing procedure (11th to 13th day) the drying process was effective in for the whole biomass layer. By that with use of the same methodology, the material would be missed each day during the whole drying process.

- The drying profile (see Figure 8.5 in Annex) and the ratio of "dry" / "wet" material (approx. 2:3, respectively) is uneven over the drying chamber. Additional "A" profile plateau between the drying channels would help to exclude the so-called "death zone" space of the drying chamber.

- The polycarbonate helio-collector has suitable heat-keeping ability but is more inclining to decrease the transparency level by outside impact in long therm. To prove this theory it would be good to measure the light throughput.

- For more precise and easier measurements the stationary measuring sensors should be installed into the selected biomass.

7. References

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8. Annexes