CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

DRYING OF BIOMASS WITH HIGH WATER CONTENT

MASTER´S THESIS

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Field of study: Power Engineering

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Declaration:

I hereby confirm on my honor that I personally prepared the present academic work and carried out myself the activities directly involved with it under guidance of Ing. Jan Havlík and Dr.Ir. Prihadi Setyo Darmanto. Cited sources of literature are perceptibly marked and listed at the end of this thesis.

In Prague, January 2017 Pavel Kovařík

Annotation page

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Abstract: This Diploma thesis is focused on the drying of biomass with a high water content. The introductory part gathers theoretical knowledge on this theme. The practical part is divided into two main parts. Firstly there is the description and the evaluation of the drying experiments, which were carried out in the laboratories of CTU. Secondly is the complete design of the rotary steam drum dryer, which is crucial for the drying of fuel, which is a precusor for its combustion in a 1 MW boiler, as given in the assignment. The Design is based on the calculation of fuel consumption in the boiler; drying process analysis and data obtained by experiments. The Conclusion of this thesis is an economical evaluation of the project.

Anotace: Diplomová práce se zabývá problematikou sušení biomasy. Úvodní část práce se zabývá teoretickými znalostmi této problematiky. Praktická část práce se skládá z dvou hlavních částí, popisem a vyhodnocením modelových experimentů sušení, které byly provedeny v laboratořích FS ČVUT, následuje návrh sušícího zařízení, které je využito pro úpravu paliva před spalováním v kotli o výkonu 1 MW. Návrh vychází z výpočtů potřeby přivedeného paliva do zadaného kotle, bilance sušícího procesu a z parametrů získaných experimentem. Závěrem této práce je ekonomické vyhodnocení uvedeného návrhu.

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Nomenclature

Symbol	Unit	Name – description
A^r	-	the ash content in the fuel (initial state)
A^d	-	the ash content in the fuel (anhydrous state)
C^r	-	the content of carbon in the fuel (initial state)
C^{daf}	-	the content of carbon in the fuel (dry ash free state)
d	m	diameter of the drum
l	m	length of the drum
h_{Ar}	$kJ \cdot Nm^{-3}$	enthalpy of argon
h_{CO2}	$kJ \cdot Nm^{-3}$	enthalpy of carbon dioxide
h_{H2O}	$kJ \cdot Nm^{-3}$	enthalpy of steam
h_{N2}	$kJ \cdot Nm^{-3}$	enthalpy of nitrogen
H^r	-	hydrogen content in the fuel (initial state)
H^{daf}	-	hydrogen content in the fuel (dry ash free state)
$h^{t,\alpha}{}_S$	kJ/kg	enthalpy of the flue gases with excess air α = 1.5 and a temperature of 150 ° C
$h_S{}^{25°C,\alpha=1,5}$	$kJ \cdot Nm^{-3}$	enthalpy of the flue gases with excess air α = 1.5 and a temperature of 25 ° C
$h^t{}_{Vmin}$	kJ/kg	enthalpy of the minimum air amount at 150 ° C
h_V	$kJ \cdot kg^{-3}$	enthalpy of saturated steam
h_{VS}	$kJ \cdot Nm^{-3}$	enthalpy of dry air
mgCO	-	emission limit for carbon monoxide
M_p	$kg \cdot s^{-1}$	nominal steam boiler output
M_{sp}	$Nm^3 \cdot s^{-1}$	the amount of input fuel
m_{pal}	$kg \cdot hod^{-1}$	required amount of fuel from the outlet of the dryer
m_{2w}	$kg \cdot hr^{-1}$	the amount of water in the dried fuel
m_{2A}	$kg \cdot hr^{-1}$	the amount dry matter
m_{1A}	$kg \cdot hr^{-1}$	the amount of input (wet) materials
m_{1w}	$kg \cdot hr^{-1}$	the amount of water in the dried material
m_w	$kg \cdot hr^{-1}$	the amount of evaporated water
$N_{pal,1}$	CZK/year	fuel costs Option 1
$N_{pal,2}$	CZK/year	fuel costs Option 2
n_1	CZK/kg	unit price of fuel Option 1
n_2	CZK/kg	unit price of fuel variants 2
N^r	-	nitrogen content in the fuel (the original state)
N^{daf}	-	nitrogen content in the fuel (the state without water and ash)

O_{Ar}	$Nm^3 \cdot Nm^{-3}$	volume of argon
O_{CO}	-	volume fraction of carbon monoxide in the fuel
O_{CO2}	-	volume fraction of carbon dioxide in the fuel
O_{CO2}	$Nm^3 \cdot Nm^{-3}$	volume of carbon dioxide
O_{H2}	-	volume fraction of hydrogen in the fuel
O_{CH4}	-	volume fraction of methane in the fuel
O_{N2}	-	volume fraction of nitrogen in the fuel
O_{N2}	$Nm^3 \cdot Nm^{-3}$	volume of nitrogen
O_{O2}	-	volume of oxygen in the fuel
O_{O2min}	$Nm^3 \cdot Nm^{-3}$	minimum amount of oxygen required for complete combustion of 1 kg of fuel
O_{O2ref}	%	oxygen content flue gases to a reference state
O^r	-	the oxygen content in the fuel (initial state)
O^{daf}	-	the oxygen content in the fuel (dry ash free state)
O^S_{H2O}	$Nm^3 \cdot Nm^{-3}$	volume of water vapor in the flue gases for stoichiometric combustion of gas
O_{SO2}	-	volume fraction of sulfur dioxide in the fuel
O_{SO2}	$Nm^3 \cdot Nm^{-3}$	the volume of sulfur dioxide
O_{SSmin}	$Nm^3 \cdot Nm^{-3}$	volume of dry flue gases
O_{SV}	Nm^3/kg	flue gases volume produced by combustion of 1 kg of fuel with excess air $\alpha > 1$
O_{SVmin}	$Nm^3 \cdot Nm^{-3}$	minimum volume of wet flue gases
$O^{ts,ps}_{SV}$	$m^3 \cdot kg^{-1}$	the actual flue gases volume
O^V_{H2O}	$Nm^3 \cdot Nm^{-3}$	volume of water vapor in humid air
O^S_{H2O}	Nm^3/kg	the volume of water vapor in the minimum volume of wet flue gases
O_{VSmin}	$Nm^3 \cdot Nm^{-3}$	the minimal volume of dry air necessary for complete combustion of 1 kg of fuel
O_{VVmin}	$Nm^3 \cdot Nm^{-3}$	minimum volume of wet air required for complete combustion of 1 kg of fuel
o_s	$kg/m^2 \cdot h$	square evaporation capacity
o_v	$kg/m^3 \cdot h$	volumetric evaporation capacity
p''	MPa	partial pressure of water vapor at the saturation temperature of the air
p_c	MPa	total pressure
Q_i	$kJ \cdot Nm^{-3}$	calorific value of the biomass
Q_S	W	gross calorific value
Q^r_s	$kJ \cdot kg^{-1}$	gross calorific value of the fuel (initial state)

Q^{daf}_s	$kJ \cdot kg^{-1}$	gross calorific value of the fuel (dry ash free state)
Q_i^r	$kJ \cdot kg^{-1}$	calorific value of the fuel (initial state)
S	m^2	are of the heated surface of the drum
S^r	-	fuel sulfur content (initial state)
S^{daf}	-	fuel sulfur content (dry ash free)
T_s	year	simple payback
V	m^3	volume of the drum
W^r	-	water content in the fuel (initial condition)
w_r	-	input moisture of the dried material
w_{r1}	-	output moisture of the dried material
z_c	-	overall unburnt losses
z_{cr}	-	unburnt losses in bottom ash - troughs
z_{cs}	-	unburnt losses in bottom ash - slag
$z_{cú}$	-	unburnt losses in fly ash
z_f	-	loss due to physical heat of solid residues
z_k	-	stack loss
Z_{SV}	-	loss due to radiative and convective heat to the surroundings
Z_{CO}	-	loss due to carbon monoxide
α	-	coefficient of excess air in the flue gas
η_K	-	overall boiler efficiency
φ	%	relative humidity
χ_v	-	the proportion of water vapor per 1 Nm^3 dry air

Introduction

Nowadays the use of fuels from the renewable sources are globally heated topics. From the globaly environmental political perspective using renewable sources as fuels are extremely important, because of its reduction of environment damage. Biomass belongs into this group of fuels. This thesis focuses on the biomass drying of wood chips, which is then used as a fuel. The most important issue of burning wood chips is its high water content in its natural state. This property hugely impacts the burning quality of this fuel. Only by drying these wood chips is it possible to decrease the water content which increases its calorific value. The main focus of this thesis is to design a dryer, which will be used for the drying of the wood chips before burning in a boiler. There are many possibilities where the drying of biomass can be used, whether as a self-standing process or as a process placed into an initial energy plant. For example, the drying of biomass can be used in a steam power plant, where overheated steam can be partially taken from the plants cycle and used as a drying medium. With the increase of biogas plants in the Czech Republic, many opportunities of applications of the drying process are rising. So, the waste heat produced by CHP units can be used as drying mediums.

1 The thesis objectives

This thesis is focused on biomass (wood chips) drying. Wood chips are used as a fuel for the boiler given by this assignment. The dryer design is based on the initial state description.

Initial state description

In a certain technological unit a biomass burning boiler with a power of 1 MWt is used as a source of heat. This boiler burns wood chips with 20% of moisture. Price of this fuel is 170 CZK/GJ. In the company´s yard waste wood is available. This wood waste has a high water content of 60% and so it is considered as unuseable waste. To run the technology of this company overheated steam is used. Low potential steam is available at the pressure of 3 bars. This thesis is focused on replacing high water content wood chips with wood waste. This wood waste will be dried using a steam drum dryer which will be designed as a part of this thesis. Further detailes of the operations will be analysed. Based on this analysis, both options of the boiler operation, with the drying and without the drying, will be evaluated economically.

Thesis objectives

- To map available kinds of biomass for energy purpose and kinds of dryers
- Drying process description
- Selection of a suitable dryer
- To run experiments in CTU labs in order to obtain drying operational characteristics
- To calculate fuel consumption in given a boiler with the power of 1 MWt, burning wood chips with 20% of moisture.
- To calculate the operational balance of the drying process, when drying wood chips from an initial moisture content of 60% down to 20%, to design the dimensions of the dryer
- Economical evaluation of a porposed dryer

The fundamentals of this thesis will be supported by reference books, consultations, and referenced sources. As a computation software MS Excel will be used. Required experiments will be run in CTU laboratories under supervisor´s supervision.

2 Biomass and its available types for energy use

The Biomass is generally organic matter, which is part of lifetime circle of living organisms in the earth's biosphere. The expression of biomass covers bodies of all living organisms, such as: plants, bacteria, cyanobacteria, fungi and finally animals.

Biomass is usually defined as plants used for energy purposes. In terms of energy, biomass belongs into well used and prospective sources of energy. It is possible to use biomass as a final source of energy; however in most cases pre-treatment of biomass is needed for it to become a fully-fledged source of energy.

Drying is the most important treatment in terms of biomass preparing. Raw biomass is mostly wet with high water content (30-60%), therefore drying is needed to decrease moisture (10-15%) and improve properties in terms of energy use. Currently the focus has been on improvement of the drying process, its operational parameters (drying curve) and emissions. Most common types of dryers are convective rotary dryers.

Energy processes using biomass:

- Chemical-thermal transfiguration
    - Combustion
    - Gasification
    - Fast pyrolysis
- Chemical-liquid transfiguration
    - Liquefaction
    - Esterification
- Biology processes
    - Anaerobic digestion
    - Alcoholic fermentation
    - Composting

With the help of these processes, useful energy can be produced from biomass, such as: heat, electricity or synfuels for transport.

The heat is mostly produced by biomass combustion; however, this process is highly complicated. Most of the time this depends on type of biomass used for combustion, and therefore it is very important to describe the types of biomass.

Types of biomass [7]:

- Agricultural biomass
    - Fytomass – plant matter
    - Dendromass – trees specifically grown
    - Specifically grown biomass – fast-growing woods
- Forest biomass
    - Firewood
    - Leavings of processing
- Residual biomass
    - Wood leavings of processing
    - Waste from cellulose – paper, wood and the furniture industry
    - Plant residues from primary agricultural production and landscape maintenance
    - Waste from food industry

For Czech Republic area, typical types of biomass are as follows:

- Wood waste and products: wood chips, sawdust, wood shavings, bark, branches and stumps
- Non-timber forest fytomass: green biomass, cereal and rape straw, energy crops
- Industrial and municipal waste vegetable - waste paper
- Animal products - manure from dung

Table 2.1 *Calorific value comparison of different types of biomass* [6]

Crop	Calorific value [MJ/kg]	Moisture [%]
Straw cereals	14	15
Straw rape	13,5	17-18
Energy fytomass - arable land	14,5	18
Fast-growing trees – ground soil	12	25-30
Energy hay - ground soil	12	15
Energy hay - a mountain meadow	12	15
Energy hay - other land	12	15
Fast-growing trees - anthropogenic soil	12	25-30
Annual plants - anthropogenic soil	14,5	18
Energy plants - anthropogenic soil	15	18

As this thesis is focused on the drying of biomass, which will be a pre-treatment of its combustion, of the previously mentioned types of biomass wood chips are a major object of interest. Wood chips are currently highly used as a source of energy for heating in industrial enterprises or other large facilities. Unlike firewood, which is mostly used as a source of energy for heating of family homes, wood chips are slowly becoming trendy for this purpose as well. Because wood chips are obtained from wood, trees or wood waste, it usually contains 40-60% of moisture in a raw state, therefore pre-treatment (drying) is needed to be able use biomass for combustion.

2.1 Wood chips

Wood chips are mechanically crushed or cut wood matter. Size of single particles may be in the range of 3 – 300 mm. Usually these chips are obtained from wood waste produced by forest logging or wood industries, and may be also obtained by mechanical crushing of fast-growing woods. These are usually artificially grown for this purpose. Wood chips are generally a low cost fuel used as a source of heat for large facilities. Based on quality and other admixtures wood chips can be divided into green, brown and white type.

Green (forest) wood chips are obtained from forest logging waste. They contain twigs, leaves or needles. The water content is high because of its raw state.

Brown wood chips are obtained from the tree trunk waste, trimmings etc. They may contain tree bark.

White wood chips are similar to brown wood chips, but there is no tree bark content. They are also obtained from the wood industry and usually they are used for particle board manufacturing. [7]

From the previously mentioned section, it is clear that wood chips are generally a forest logging waste, therefore the water content is high, mostly 50-55%. Density of wood chips is approximately 300kg/m^3. Calorific value strongly depends on water content and it may be in range 5,9 - 15,1 MJ/kg^{-1}.

Biomass as a fuel for combustion is characterized by following features [16]:

- calorific value
- water content
- ash content
- composition of combustibles
- the ratio of volatile matter
- the composition of the ash - Cl, heavy metals,
- temperature of the softening, melting and flow of ash

2.2 Biomass composition:

The dominate chemical composition of biomass are organic substances and water. It also contains incombustible minerals (ash), but only in small amounts. The basic elements of biomass are: carbon, hydrogen, oxygen and nitrogen. The organic matter contained in the biomass generated by air, water and minerals from the soil during its growth. The following table shows the elemental compositions of multiple kinds of biomass.

Table 2.2 *Chemical composition of multiple biomass kinds* [9]

Chemical composition			Wood chips		Straw		Grasses	
Parameter		Unit	Average	Range	Average	Range	Average	Range
Carbon	C	%	50,0	49 - 52	47	46 - 48	48	47 - 49
Hydrogen	H	%	5,8	5,2-6,1	5,9	5,3 - 6,4	6,5	5,5 - 6,8
Nitrogen	N	%	0,3	0,1 - 0,7	0,7	0,3 - 1,5	1,1	0,7 - 3,1
Sulfur	S	%	0,1	< 0,1	0,1	0,05 - 0,3	0,1	0,05 - 0,3
Oxygen	O	%	41	39 - 43	41,8	40 - 42	39	36 - 41
Combustible volatile matter		%	81	70 - 85	78	75 - 81	76	74 - 82

Ash content in biomass is low, usually in range 0 - 1%. These minerals originate from a soil. That makes biomass a good fuel for wood gas boilers with ideal combustion. Ash produced by combustion is formed by these minerals and coarse dirt brought into combustion with fuel. [10]

2.3 Water content in biomass:

Water content of biomass is the most observed element. It strongly affects calorific value, temperature of combustion, volume of produced flue gasses, dew point temperature of flue gasses and boiler efficiency. Relating to the energy perspective it is generally an effort to reach best values of previously mentioned features.

Water content in biomass is usually named as moisture. It is a percentage value of water content weight and total biomass weight ratio. Moisture of wood and biofuel can be expressed as a ratio of water content weight and dry wood weight. Therefore, it is important to state how moisture is expressed.

Water content effect on calorific value is described by the following formula:

$$Q_i = Q_s - 2453 \cdot (W^r + 9 \cdot H^r)\ [kJ/kg]$$ [16] (1.1)

Where: Q_i …. biomass calorific value

Qs … gross calorific value

W^r… water content

The following table shows calorific values comparison of multiple kinds of biomass depending on the water content:

Table 2.3 *Calorific value - chemical composition dependence* [16]

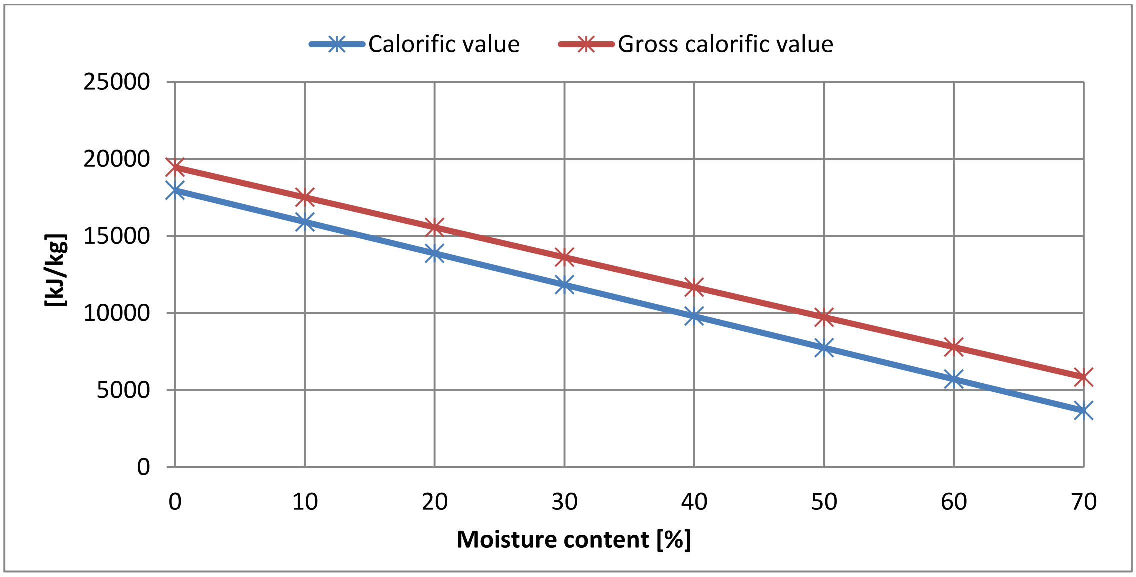
Chemical composition		Wood chips		Straw		Grasses	
Parameter	Unit	Average	Range	Average	Range	Average	Range
Water content *Wr*	%	45	20-60	14	8-23	14,5	10,5-21
Ash content *Ad*	%	1,1	0,3-6	4,5		5,3	3,8-8
Combustible volatile matter *hd*	%	81	70-85	78	75-81	76	74-82
Calorific value	$MJ.kg^{-1}$	9,5	15-6	115	16-12	15	15-11

The following graph shows the impact of water content on combustion process properties. Calculations were performed for given fuel, its composition is as follows:

- Gross calorific value $Q_s = 19769\ kJ \cdot kg^{-1}$
- Moisture $W = variable$
- Ash content $A^d = 1{,}61\ \%$
- Carbon content $C^{daf} = 50{,}9\ \%$
- Hydrogen content $H^{daf} = 6{,}93\ \%$
- Nitrogen content $N^{daf} = 0{,}26\ \%$
- Sulfur content $S^{daf} = 0{,}003\%$
- Oxide content $O^{daf} = 41{,}8\ \%$

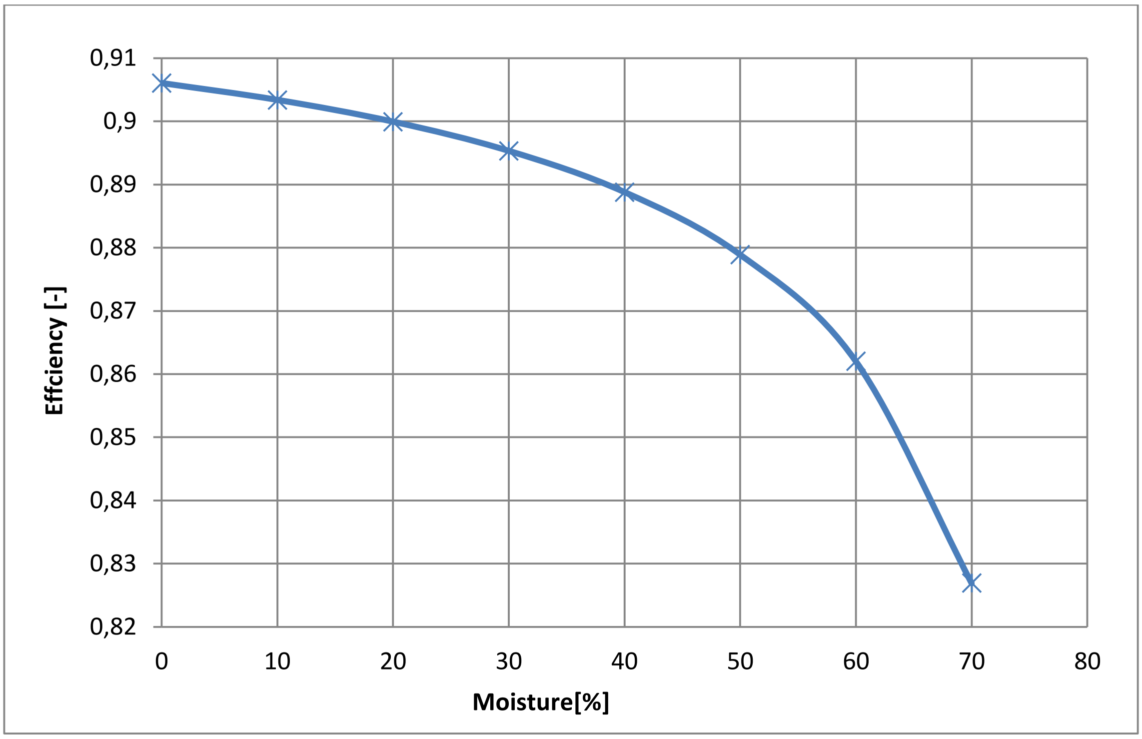
This composition of fuel is used for calculation in chapter 6.

Graph 2.1 *Moisture to calorific value dependence*



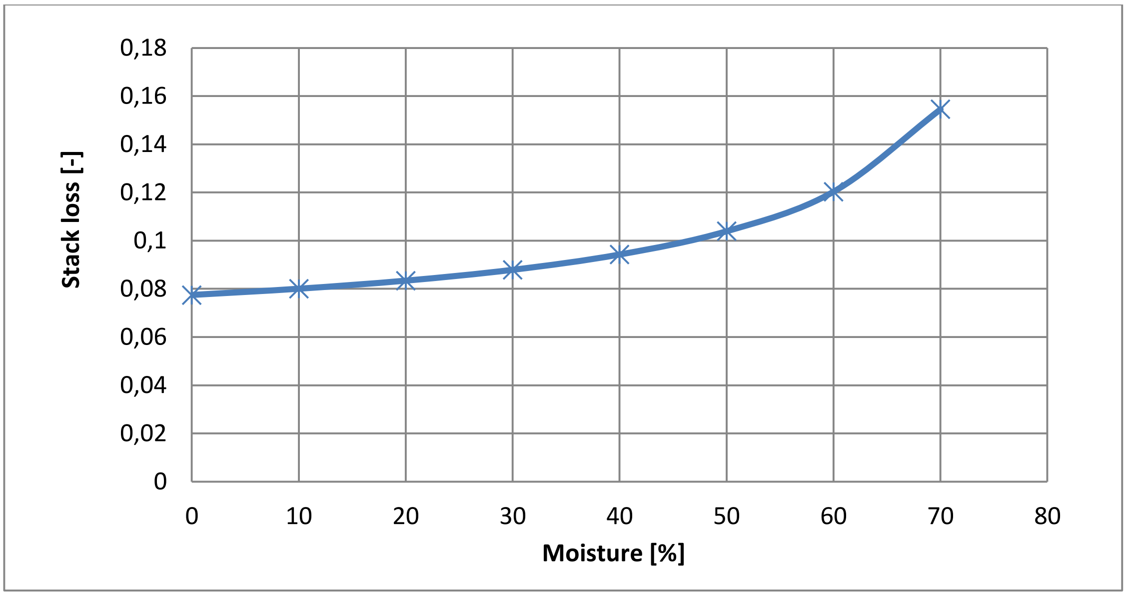
Calorific value and gross caloric value of given fuel are directly proportional to moisture of fuel. In mentioned graph it is possible to observe radical drop of calorific value and gross caloric value when the moisture fuel is rising. Calorific value is main rating factor of the fuel. Calorific value strongly affects price of biomass.

Graph 2.2 *Moisture to boiler efficiency dependence*



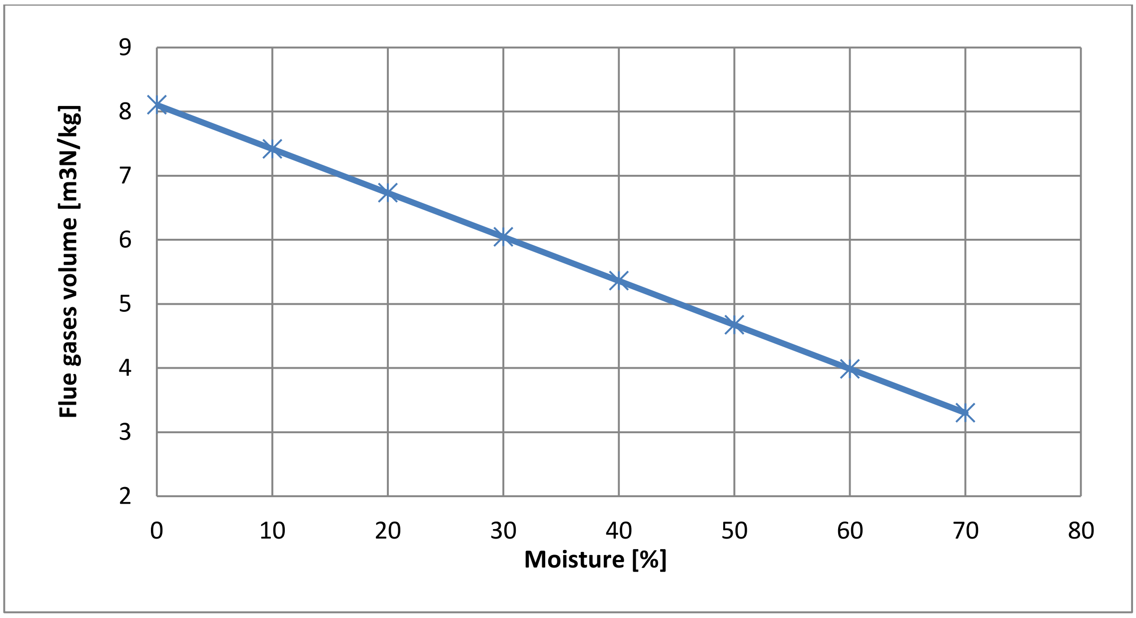
Water content in the fuel has a high impact for a boilers efficiency. With the rising moisture of fuel, the boilers efficiency is dropping. It is possible to observe a steep drop of efficiency in the range of 40 – 70 % of fuel moisture. When the moisture is less than 40% the drop becomes noticeably gradual.

Graph 2.3 *Moisture to stack losses dependence*

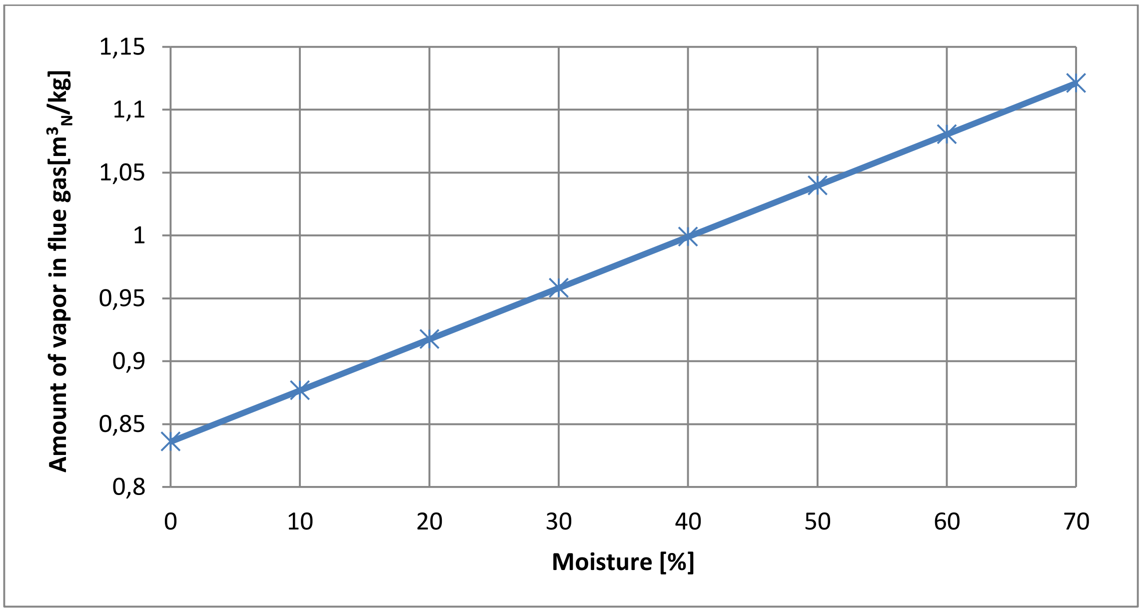


Stack loss is important parameter in boiler efficiency calculation. It has the highest values comparing to the other partial losses. Because of this high impact, dependence between stack loss and moisture was being observed. When the moisture of fuel is under 40%, stack loss rises gradually. When the moisture of fuel is more than 40 % stack loss rises significantly, which affects boiler efficiency.

Graph 2.4 *Moisture to flue gases volume dependence*



Graph 2.5 *Moisture to vapor amount in flue gas dependence*



From the graphs shown, it is obvious that water content in biomass is a highly important parameter. Both calorific value and gross calorific value are affected by moisture, but also the quality of combustion is strongly affected. Boiler efficiency drops rapidly with a rise of moisture in fuel. There is a moisture level limit which defines the highest moisture level for fuel to be combustible. Value of this limit is slightly different for multiple kinds of biomass, but generally it is 55% of moisture in the fuel.

Fuels with moisture of 20% and less are well combustible. It is possible to burn fuel with higher moisture than 20%, however boiler efficiency drops and fuel consumption rises.

2.4 Biomass water content

Water appears in biomass in three different forms. That is a very important fact according to drying of biomass. These three forms are:

Bounded chemical water – it is part of chemical compounds. It is not possible to eliminate this water by drying, only by burning. This element is almost negligible in range of absolute moisture.

Bounded water – it is part of cell walls. It appears in fuel with 0-30% of moisture. This element has strong impact on physical and mechanical properties.

Free water (capillary) – it fills intercellular space. There is less impact on physical and mechanical properties in compare with bounded water. [4]

2.5 Biomass moisture measuring

Biomass moisture measuring is the most important factor during evaluation of fuel quality. There are multiple methods of moisture measuring, based on technological progress.

- Moisture determination by dividing of water and solid phase
  - Gravimetric method
- Moisture determination based on the specific properties of water
  - Spectrometric Method
  - The method of nuclear magnetic resonance
  - The method absorption of gamma and X-rays
  - Attenuation measurement of microwave energy
- Measurement of other variables related to the content of water
- Resistive, capacitive, inductive

The most accurate moisture determination method is the gravimetric method. It is also most common method in this field. This method is based on characteristic moisture formula:

$$w_{abs} = \frac{m_w - m_o}{m_o} \cdot 100$$ [4] (2.2)

The principle of this method is measuring of wet biomass weight $\mathbf{m_w}$ and absolutely dry wood weight $\mathbf{m_0}$. After that comes drying, during which biomass sample weights are measured. This process allows monitoring of drying progress. The end of the drying process is defined by 2 measurements with weight difference less than 0,02 g (less than 1%).

The advantage of gravimetric method is its high accuracy. Disadvantages are duration and impossibility of continual measuring.

There are many kinds of devices used with gravimetric method principles. For example, halogen or infrared drying scales. The advantage of these devices are the speed and continuality of heat, also weight measure accuracy of input material.

Indirect methods of moisture measuring are used in case of continual measuring. These are used for measuring during every day heating plants service. Calibration of devices is needed, which has strong impact on measuring accuracy.

3 Drying process description

Drying of biomass is a very intensive process from an energy perspective. It consumes a large amount of heat and electrical energy. During this process the water content is eliminated from the material. There are many linked processes of heat transfer and matter transfer (between drying medium and material). Heat transfer is provided by convection from drying medium to material. Transfer of matter a diffusive process is in this case.

Input biomass for drying usually contains moisture of 30-60%. This depends on type, place and period of logging, and also on storing duration. Size of single particles depends on energy purpose of biomass. Usually the particle sizes are in range of 10 – 80 mm. In steam drum dryers it is possible to dry a larger range of particles. Unlike band or fluid dryers, particles smaller than 10mm are necessary to allow for better drying transition. Density of material is in range of 50-400 kg/m^{-3}, and again depends on moisture content of the material.

3.1 Sources of heating for drying

Evaporative drying processes require heat exchange by convection or conduction. Possible sources of heat for drying are hot furnace, engine or gas turbine exhaust gases, high pressure steam from a steam or combined cycle plant, warm air from air cooled condenser in a steam or combined cycle plant and steam from dedicated combustion of biomass, biogas or bio-oil. The dryer can be a stand-alone process or integrated with, for example, district heating network, pulp mill, saw mill or combined heat and power plant.

3.2 Emissions of drying process

During biomass drying organic compounds are released, which is caused by volatilization, steam distillation and thermal destruction. These compounds cause emissions into the air or wastewaters.

The organic compounds emissions can be divided into volatile organic compounds and condensable compounds. When drying temperatures are low (under 100°C), emissions are mostly consisting of monoterpenes and sesqviterpenes. The volatile organic compounds are an environmental concern, as they form ground level ozone in the presence of nitrogen oxides. Photo-oxides are also harmful to humans, as they cause irritation in the respiratory tract. The condensable compounds, such as fatty acids, resin acids and higher terpenes, can cause device damages when the drying temperatures are over 100°C, they condensate on device surface.

In direct dryers using flue gas as a drying medium, temperature is relatively higher and emitted organic compounds leave with flue gas through the chimney. These dryers are the most common types used for biofuel drying. It is also possible to further use flue gas as a low potential heat source. Flue gas cleaning devices can be used, but this depends on applicable emissions criteria and regulation, characteristic to location. Solid particles are usually eliminated by cyclones or bag filters.

If drying temperatures lower than 100°C can be maintained, it is possible to reduce water content to 10% of moisture in material, without emitting a harmful amount of organic compounds. [3]

3.3 Drying temperature

Temperature of drying is an important parameter in the drying process analysis. Low-temperature drying brings significant advantages as opposed to high-temperature drying. Low-temperature drying allows utilization of low-potential heat, which can be produced as a waste product of other processes. Using heat produced by renewable sources of energy can be advantageous. Dryer heat losses decrease using low-temperature drying. Low-temperature drying brings significant economic advantages together with reduced drying emission amounts. For example, overheated steam bark drying produces organic compounds together with waste water. High-temperature drying of spruce and birch causes evaporation of volatile mutagen compounds. In general, hot air or steam drying releases mainly monoterpene and sesqviterpenes hydrocarbons. Increase of drying temperature can accelerate this process; however heat losses of dryer increase as well. In general maximum temperature is given by kind of material and drying process. In the case of fluid drying the material is in continual move and overheating of local points are excluded. In this case of drying, higher temperatures can be used. [3]

3.4 Drying statics

Describes matter and heat balance between material and drying medium.

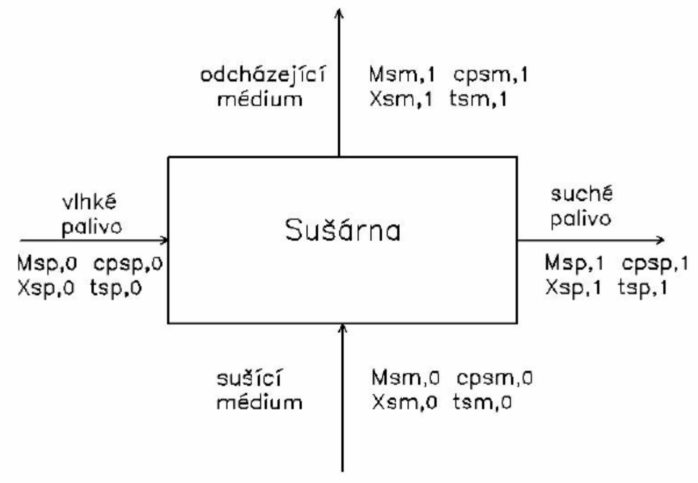


Figure 3.1 *Drying balance* [2]

Matter balance:

$$M_{sm,0} \cdot X_{sm,0} + M_{sp,0} \cdot X_{sp,0} = M_{sm,1} \cdot X_{sm,1} + M_{sp,1} \cdot X_{sp,1} \tag{2.1}$$

Matter flow rate:

$$M_{sm} \cdot (X_{sm,1} - X_{sm,0}) = M_{sp} \cdot (X_{sp,1} - X_{sp,0}) \tag{2.2}$$

Energy balance:

$$Q = M_{sm} \cdot (i_{sm,1} - i_{sm,0}) + M_{sp} \cdot (i_{sp,1} - i_{sp,0}) \tag{2.3}$$

M_{sm} – amount of drying medium

M_{sp} – amount of material

X_{sm} – drying medium moisture

Q – heat given into drying process

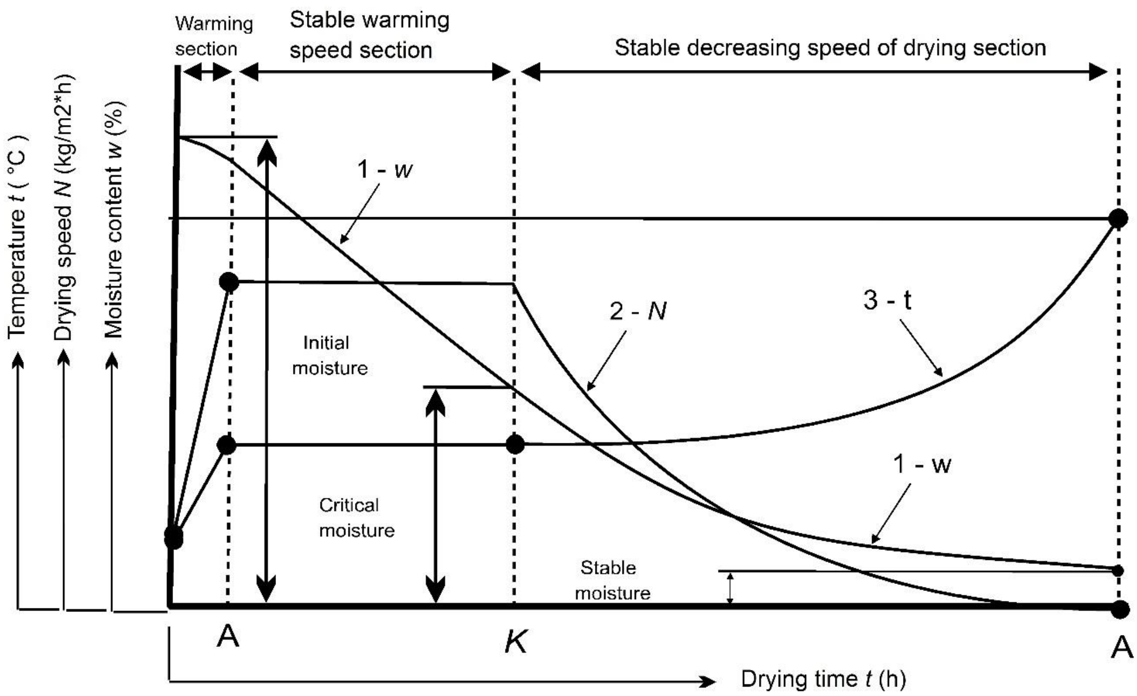
i_{sm} – entalphy of drying medium

i_{sp} – entalphy of material

3.5 Drying kinetics

As drying is a heat and matter transfer process, propulsive matter force and heat force do exist. Both these forces affect drying process. Based on this fact, drying kinetics can be described. It is most effective to describe drying kinetics by drying curve. Basically drying process can be divided into 3 main parts.

Graph 3.1 *Drying kinetics* [8]



- **1. Part – warming on evaporating temperature –** as air is ineffective heat conductor, most of heat energy has been absorbed in materials surface water. During this period heat transfer is low.
- **2. Part – constant drying speed** – at the point when larger amount of heat energy has been absorbed, water on the surface of material is changed into vapor. That is evaporation with a heavy matter transfer. As long as matter transfer is constant, it is a constant evaporation. This part ends by moisture decrease in material from initial value to critical value. At this point, wet and dry regions start to appear on materials surface.

- **3. Part - Decreasing drying speed –** as wet and dry regions start to appear, diffusion begins. Diffusion is slow matter transfer process, in contrast with evaporation. Matter transfer is non-linear decreasing at this point, until reaching final moisture value.

Drying statics explain only dryer function in general and its heat consumption. Kinetics of drying on the other hand explains more deeply the drying process analysis. For different kinds of dryers, there are different types of analysis. In the case of direct dryers, analysis is focused on a thin layer of material, unlike in indirect dryers with stationary layer, the focus is on temperature and moisture distribution in material and drying medium. For each type of dryer, experiments and its data are needed.

In general, this experiment is drying for a given material with constant parameters of drying setting. Obtained specific moisture X_s, on time dependence is labeled as the drying curve below.

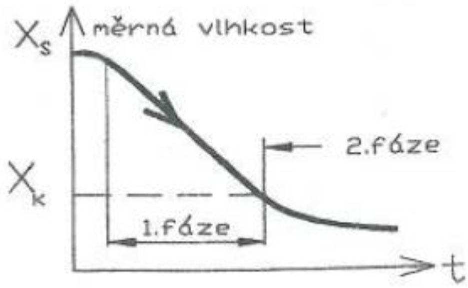


Figure 3.2 *Drying curve* [2]

Speed of drying is negative time derivation of specific moisture X_s.

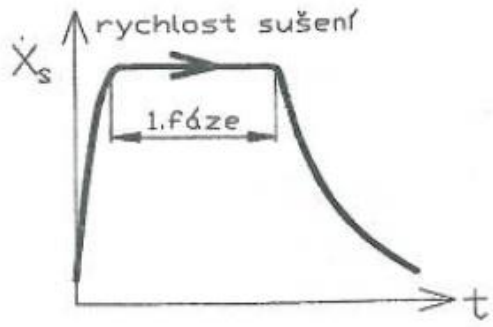


Figure 3.3 *Drying speed* [2]

The dependence of drying speed $\dot{X}s$ on specific moisture X_s. is showing basic drying curve. This basic drying curve can be used for real processes description. For first phase, drying modeling is needed, and then the results are multiplied by dimensionless drying speed. The shape of basic drying curve can be approximately replaced with a straight line and after that time on material moisture dependence can be expressed analytically.

The only case where drying process modeling is not needed is running of experiment in quarter-scale operational settings and determines an operational drying curve. Operation parameters such as drying time, temperature and inlet-outlet materials moisture are similar to purposed drying process. However, results of this experiment might not be similar to real processes. It is important to stand the same drying medium flow rate, material and air flow rate ratio.

4 Types of biomass dryers

Biomass dryers can be classified by various criteria, for example, according to drying principles [15]:

- Direct - convective
- Indirect - conductive
- Radiant (electromagnetic devices)
- Combined

According to design:

- Cylindrical
- Rotary
- Disc
- Tubular
- Blade
- Special

According to operation:

- Continual
- Discontinuous

Dryers are mainly classified according to used drying medium. The most common types are flue gas or superheated steam dryers. Those two drying medium are widespread. Flue gas dryers are mainly rotary and flash. The commercial scale steam dryer types are tubular dryers.

According to previously mentioned distribution, two basic heat transfer criteria are conductive and convective.

Conductive or indirect dryers use heat transfer by direct contact between materials on a heated surface. The drying medium and the dried material are separated by heated surface. Overheated steam is the main source of heat. However, electric power can be used as well. Unlike convective drying, heat resistance is low. Moisture is being vaporized by a drying medium. The waste heat and flue gases can be re-used.

Convective dryers use hot air or hot flue gases as a drying medium. These are going directly through the layer of material. Heat and mass transfer is happens inside the drying space.

4.1 Drum steam dryer

Rotary dryers with indirect heating use overheated steam as a heating source. Although the most common case of this type of drying is drum steam dryer with indirect heating. Steam flows inside of pipes which encircle drying chamber. The number of pipes depends on parameters and shape of given dryer. Pipes are fixed to the dryer by fixing elements. Heat transfer is provided by conduction on the surface of material at the evaporating temperature. Usually saturated steam is being used at the pressure of 0,6 – 1 MPa. Steam condensate as flows through the dryer, therefore dryers have collectors of condensate water.

Figure 4.1 *Steam drum dryer* [13]

4.2 Rotary cascade dryer

The direct rotary cascade dryer is another common type of dryers used by large scale plants. The dryer is consist of large horizontal tube and inclined rotating cylindrical drum. Material is moving inside of the drum. The drum diameter may be in the range of 1 – 6 meters, depends on design. Material is coming in at the upper end, going through whole length of drum and coming out from the dryer at the lower end. The drying medium, either heated air or flue gases, may flow either way, although parallel flow is usually necessary for heat-sensitive materials, including biomass.

Figure 4.2 *Rotary cascade dryer* [14]

Following scheme shows an example of steam drum dryer application. The drying medium is overheated steam. Dryers allow large scale parameters compatibility of heat source; therefore various heat sources can be used. Emissions produced by drying process are low.

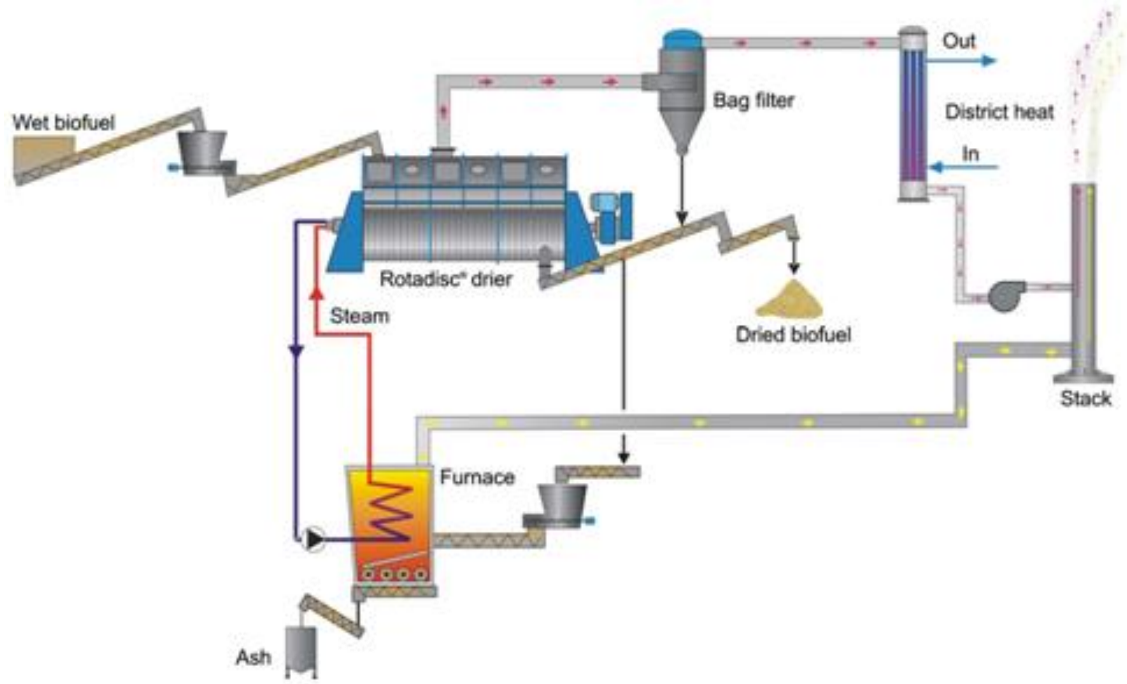


Figure 4.3 *Dryer application scheme* [12]

4.3 Perforated floor dryer

The perforated floor dryers are usually in discontinuous or batch mode, although it may be configured to operate in continuous mode. Discontinuous type has low capital cost, therefore is more attractive. The dryer is suitable for to small plants of perhaps 3 MW or less

The basic system consists of perforated floor, with heated air going through. Heated air is a drying medium. Flue gases contains great amount of moisture; therefore they cannot be reused. The wet material forms a fixed bed depth of 40-60cm above the perforated floor. The batch time is typically a few hours. [3]

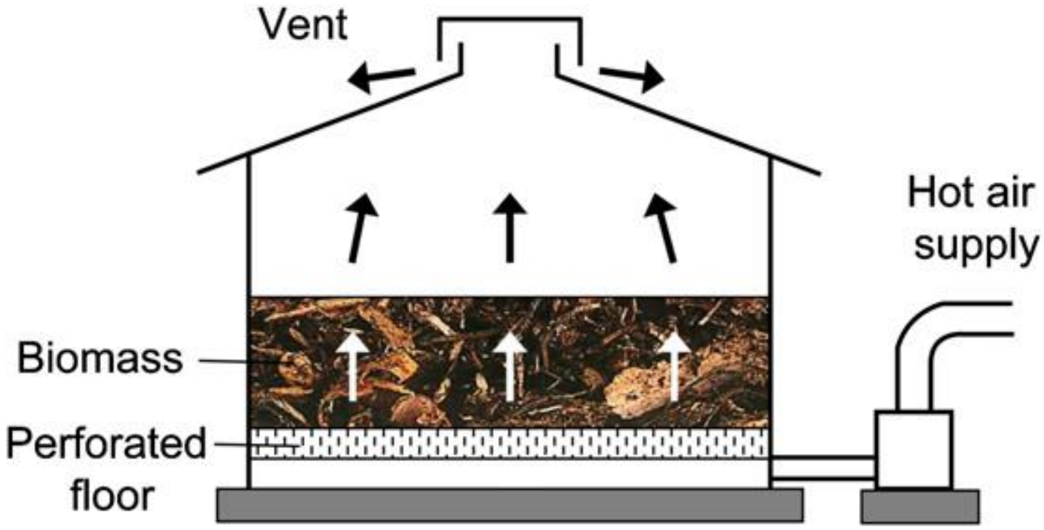


Figure 4.4 *Perforated floor dryer* [3]

4.4 Fluid dryer

Convective fluid dryers use heated air of flue gases as a drying medium. In fluid dryers a drying medium is going through the layer of material particles. The speed of air flow is determined to float the particles layer. This type of drying is fast and effective in general. Components of dryer are relatively small comparing to the other types of dryers. Material has to be crushed before drying in fluid dryers. Crushing device brings higher investment costs.

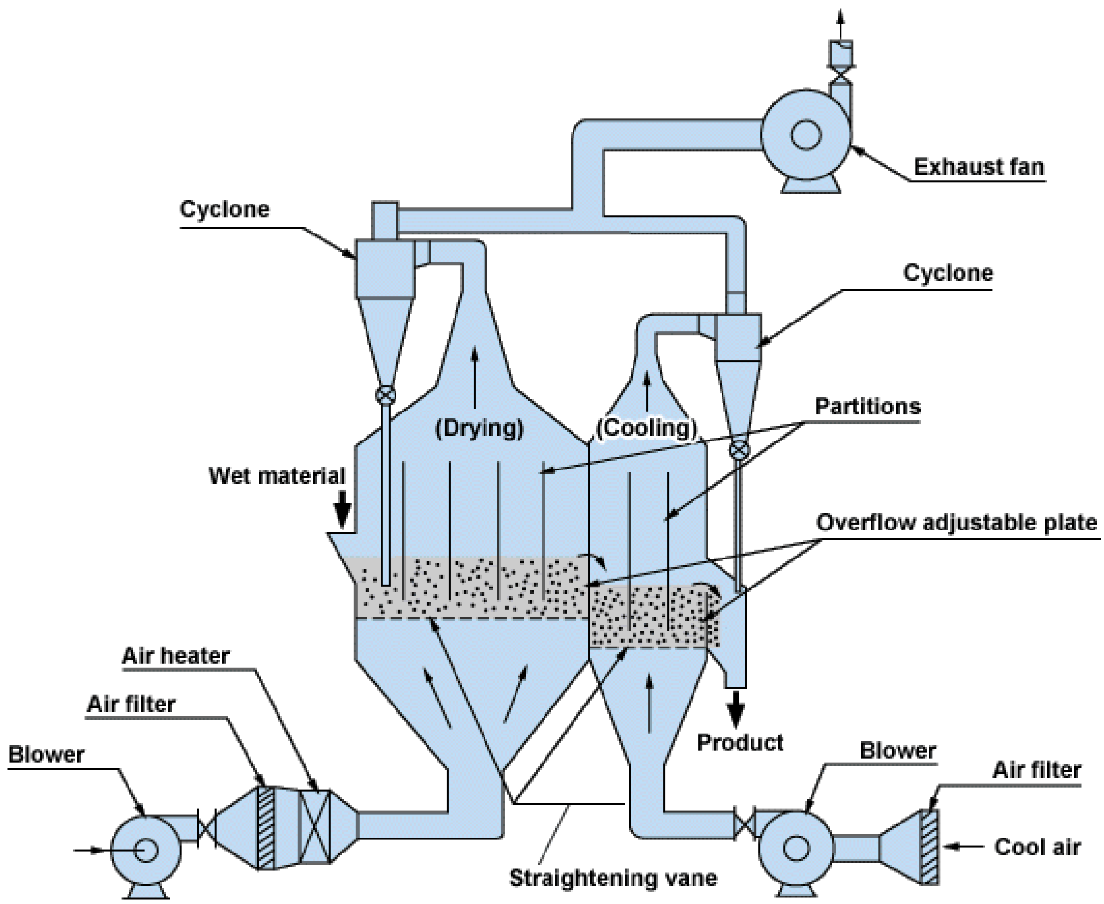


Figure 4.5 *Fluid dryer* [17]

4.5 Band conveyor dryer

The continuous dryers which use through circulation of drying medium are the most common drying devices. In this dryers, drying medium flows through a thin layer of material. Material lays on the band conveyor. Drying medium may flow upward or downward. Band conveyor dryers may be multi-stage or single-stage version. In multi-stage design, a number of bands are arranged in series horizontally. The drying medium is usually used either heated air or flue gases. In both cases drying medium is forced through the dryer by fans. Heated air is provided by hot water or steam at low pressure in heat exchanger. [3]

Band dryers are controlled by regulation of basic parameters, residence time, moisture content and maximum temperature of the product. Well uniformity of drying is caused by relatively thin layer of material on the band (usually in the range 2-15 cm). Comparing to the other types of dryers, band dryers are voluminous and spacious constructions. Size and cost of dryer strongly depends on particle size of the drying material. Sawdust dryers are smaller band dryers comparing to wood chips band dryers. Maximum temperature of drying medium (heated air) is typically 90 – 120°C.

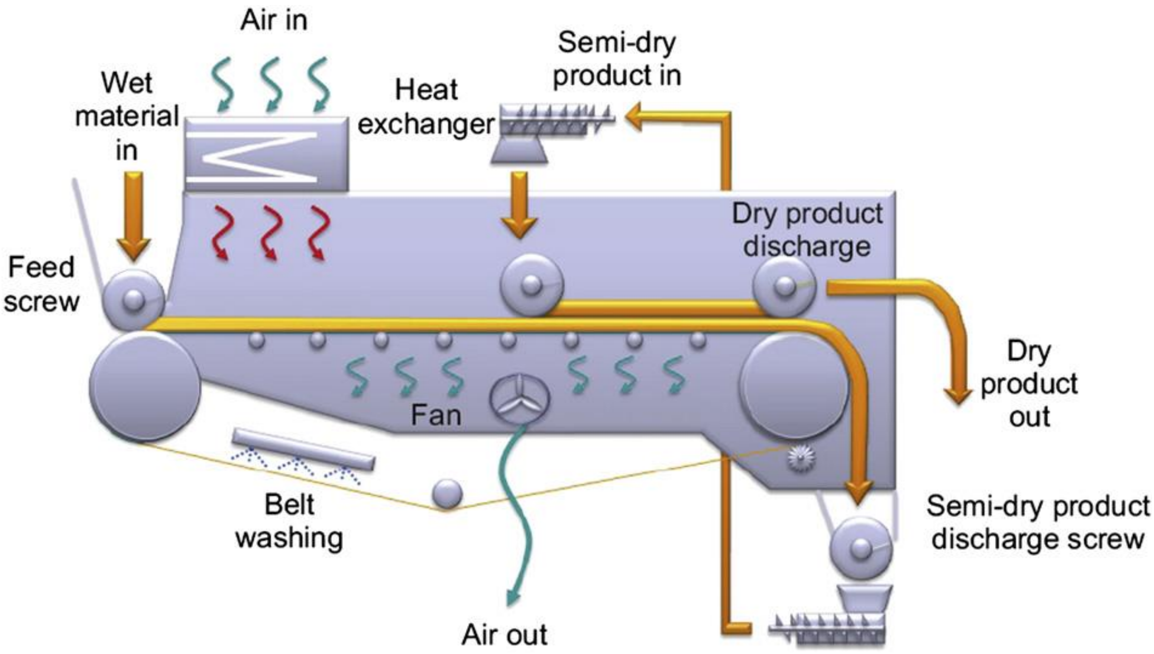


Figure 4.6 *Band conveyor dryer* [11]

Table 4.1 *Performance data for dryers applied for biomass* [3]

Dryer	Band dryer	Rotary	Steam rotary	Fluid
Feed	sawdust, wood shavings, wood chips	sawdust, wood chips, bark	sawdust, wood processing	wood chips
Feed flow (t/h)	8-9	6-7	5-6	9
Moisture inlet (%)	50-60	50-61	50-62	50-63
Moisture outlet (%)	10-15	10-15	10-15	10-15
Drying medium	air, flue gas (90-120°C)	air, flue gas (250-400°C)	steam (p-atm), steam (0,6-1 MPa)	steam (2,6 MPa)
Evaporation capacity (t/h H_20)	10	7-8	6-7	5-40
Energy consumption (MJ/kg H_20)	4-5	4-5	3-4	

4.6 Suitable dryer type selection

The first step of biomass dryer design is choice of suitable dryer type. Band conveyor dryers are suitable for low-temperature drying or heat recovery drying. Unlike rotary dryers, which are usually operating at the range of temperature 250 – 400°C. Band conveyor dryers can operate with very low temperatures, like 10°C over the ambient temperature. Usually they operate with temperatures 90 – 200°C. Risk of fire or emission is very low in band conveyor dryers because of low-temperature drying.

Nowadays the steam used as a drying medium becoming very attractive due to its high energy efficiency, low fire risk and low environmental impact. Steam dryers are usually band or fluid type, however steam drum dryer is also possible type. Overheated steam in this dryer provides energy needed to evaporate the moisture out of the material. Material is mixed with certain amount of overheated steam and evaporated moisture is leaving as a saturated steam. Disadvantage of this type of dryers is small particles request and also higher investment costs of stainless steel components and waste water cleaning device.

Based on the observation of the previous table and the dryer types comparison, the steam drum dryer was choosen for the purpose of this thesis. The objective of this thesis is to design a steam drum dryer, which will be used for fuel (wood chips) and pre-treatment (drying). In comparison to other types, the steam drum dryer has the lowest evaporation energy demand. As overheated steam is available for drying, the steam drum dryer is the most suitable type.

The design of the dryer is very specific. It is not based on any convetional method. Also, steam drum dryer´s are not not very common. The design is based on the results of the experiments. These will be conducted in CTU labs, where a scaled steam drum dryer is available.

The important part of designing the dryer are the experiments. Operational characteristics are obtained by these experiments. Based on operation characteristic, a dryer can be designed. In the CTU laboratory, all the experiments were achieved resulting with dryer type giving the required range of drying medium parameters.

5 The experimental determinations of operating characteristics of the biomass contact dryer

The following chapter describes the drying experiments, which were performed as a part of this thesis in the CTU laboratories. Based on the evaluation of these experiments, the operation characteristics were transferable and collated.

5.1 Experiment description

The sole purpose of these experiments was to run multiple drying processes by using the steam drum dryer. This device is an inclusive machine of the CTU laboratory equipment. Wood chips were obtained from various sources and used soley for our experiments. The drying medium of these chips was from a side piping which provided steam. This piping was supplied by a nearby heating plant. Identical parameters for the drying and the material (wood chips) were used for all experiments.

Figure 5.1 *Steam drum dryer, CTU laboratories*

5.2 Experimental procedures

First stage of experiment procedures was to warm the steam piping until it became close to the operational state parameters. Then opening the main valve, steam was distributed into the all of the piping, then the secondary valves were opened to obtain a continuous warming up of whole piping. The pipelines were warmed until the steam reached the operational parameters. The requested parameters were controlled by the main valve and by the manipulation of the reduction valve situated outside of the dryer.

During the warming process of steam pipelines the preparation of the biomass (wood chips) for drying was started. This material was exposed to outside conditions, e.g. snow, wind, rain which ensured the correct water content of the material and then placed into the steam drum dryer. This experiment was repeated 6 times with same material. As a part of the experiment it was essential to mix the materials for separation of the samples. A quartering method of the samples was used and then samples were placed into the hot air dryer for a prescribed period. Separated samples were placed into hot air dryer for certain time period. A calibrated device, which is a standard feature of CTU laboratories was used for the measuring of the weight of the samples.

Figure 5.2 *Measuring of samples weight*

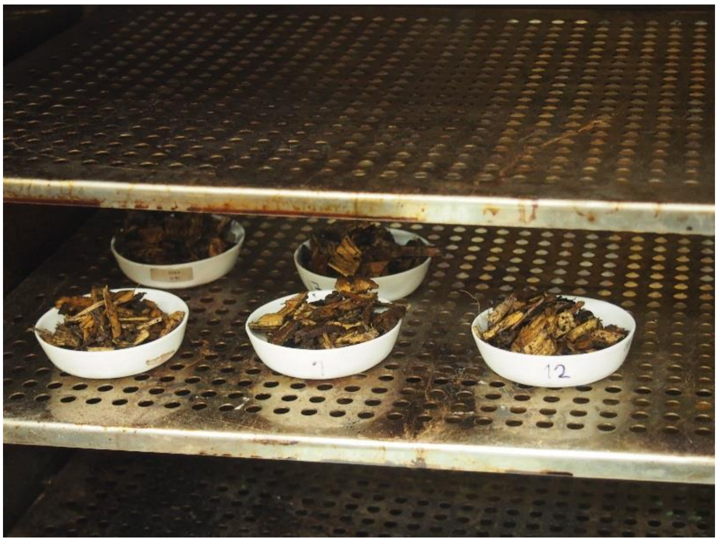


Figure 5.3 *Material samples*

Figure 5.4 *Hot air dryer*

To start the experiments, the dryer was warmed. By opening a valve, steam was distributed which enabled the dryer to spin without any material and heat faster. The temperature was recorded by the integrated thermometer. When the operational parameters were reached at that point the actual experiment could start. All experiments were started at the same predetermined time (conditions), so that it was possible to monitor the entire processes and its secondary actions consequences. All data was recorded and evaluated by computing technology. The start of the experiments was settled by placing the wet material into the automatic scroll feeder. Total volume of material was loaded into the dryer as quickly as possible (7-10 min). The circulation of the material in dryer was ensured by the returning of the output constant volume container back into input of the dryer. Every load of the output container was weighed and at each stage of weighing the data was recorded. Based on this data a graph of the drying curve was enabled to be maid. The returning of the material from the output to the input incurred negligible losses. During the experiments the temperatures inside the chamber and the volume of evaporated water were recorded.

Figure 5.5 *View of the drying chamber*

The inner space of dryer contains a rotating steel drum which is heated by steam inside its pipes.

There was a deliberate variation on all of the experiments. The final data was reached by using time intervals and by the values of the material weighed. When the values became uniformed the experiments ended. All the results are shown on Table 5.2. After the end of each of the 6 experiments the total volume of the material was weighed and again quarted samples were taken and placed into the hot air dryer. The input and output moisture contents were obtained based on the data from all sample measurements. The whole experiment ended with the closing down of the steam drum dryer.

Figure 5.6 *The visual contrast of raw and dried wood chips*

On left side is raw material before drying and on the right side is dried material.

Table 5.1 *Common parameters of all experiments*

Dryer dimensions		Drying medium parameters	
Drum diameter (m)	0,6	Steam temperature (°C)	135
Drum length (m)	2	Steam pressure (bar)	3,2
Inner surface area (m^2)	6,28	Steam enthalpy [kJ/kg]	2727
Drum volume (m^3)	1,57	Evaporated water enthalpy [kJ/kg]	567
		Transferred heat [kJ/kg]	2160

5.3 Experimental output data

The data obtained by the experiments are very useful for the designing of the dryer. It is possible to observe variability of each experiment. The main difference between the experiments was the amount of material used. The amount values were in range of 20 – 60 kg. The input moisture of material was very similar for each experiment. The volume of the moisture was in range of 62 - 65%. The comparison of the output moisture to the input moisture of the material varied for each experiment. This was the result of the variable drying time for each experiment.

The two most important parameters in terms of designing dryers are the square and the volumetric evaporation capacity. These refer to the heating area and the volume of the dryer. The exact dryer dimensions can be calculated based on these two parameters.

The consumption of energy drying is another very important parameter, which defines the amount of energy needed to evaporate 1 kg of water from material.

Table 5.2 *Experiments output data*

Experiment	Amount of input material (kg)	Input moisture (%)	Water content (kg)	Amount of output material (kg)	Output moisture (%)	Evaporated water (kg)	Square evaporation capacity (kg/m²*h)	Volumetric evaporation capacity (kg/m³*h)	Energy consumption (MJ/kg_w)
Experiment no.1	21,6	62,2	13,4	12,55	20,3	11,8	1,88	7,54	3,21
Experiment no.2	23,2	62,2	14,4	11,1	18,2	12,1	1,93	7,70	3,24
Experiment no.3	34,5	62,2	22,2	12	4,17	22,5	1,63	6,51	3,52
Experiment no.4	38,8	64,2	24,9	12	3,68	25,3	1,71	6,85	4,47
Experiment no.5	63,5	65,5	41,6	23,3	14,7	40,2	2,08	8,30	3,43
Experiment no.6	65,0	60,5	39,4	25,1	16,9	39,9	1,99	7,95	3,00

Table 5.3 *Operational parameters of drying*

Experiment	Drum rotation (rot/min)	Drying duration (min)	Dryer content (%)
Experiment no.1	4,3	60	-
Experiment no.2	4,3	60	-
Experiment no.3	2,9	138	14,4
Experiment no.4	2,9	173	19,6
Experiment no.5	2,9	205	27,4
Experiment no.6	1,4	217	27

Previous tables show the collection of experiment output data. As it was mentioned before, all experiments were conducted at different conditions, either amount of material or drum rotation and drying duration. All of these parameters were change purposely to obtain objective results and better understanding of drying process. Considering dryer design, the most valuable parameters are, evaporation capacities and energy consumption of drying.

Square evaporation capacity $o_S = \frac{m_W}{S}\ [kg/m^2 \cdot h]$ (5.1)

This parameter is based on shown formula, where $\mathbf{m_W}$ presents the amount of evaporated water and **S** presents inner surface of dryer. For all experiments exactly same dryer was used, therefore parameter S is constant. Unlike amount of evaporated water, which was various for each experiment. This fact is result of various amount of material for each experiment.

Each experiment has various time duration, therefore equation (5.1) was modified to be possibly used for experiments 3 – 6.

$$o_S = \frac{\frac{m_W}{S}}{\frac{T}{60}}\ [kg/m^2 \cdot h] \quad (5.2)$$

parameter **T** represents time duration of drying process in minutes. Total time was determined from observing of progress of change materials weight at constant volume, so that refers to drying process. That means time duration, when material was dried from input moisture to output moisture. When material wasn´t dried anymore, experiment ended.

For each experiments have been determined values of total time duration, as it is mentioned in previous table.

Other parameters, which weren’t constant for each experiment are, drum filling and drum rotation. These must be considered in final evaluation.

Based on all experimentally obtained parameters, the square evaporation capacity can be evaluated and compared. The highest value of volumetric evaporation capacity reached experiment no.5. It is obvious that drum filling has certain impact to this parameter. Also drum rotation has impact to square evaporation capacity. By drum rotation reduction square evaporation capacity raises. However it is obvious that dryer filling has greater impact to square evaporation capacity. This is concluded from experiment no. 5 and no. 6 comparison.

Volumetric evaporation capacity $o_S = \frac{m_W}{V}$ [kg/m^2 · h] (5.3)

This parameter is similar to square evaporation capacity. In this case evaporation capacity refers to volume of the dryer. Therefore evaluation of this parameter may be similar as previous.

Experiment no. 5 has reached the highest value of volumetric evaporation capacity, thus show the ability to evaporate at same conditions, such as time duration and size of dryer, the highest amount of water from material, comparing to the other experiments.

Energy consumption $Q = \frac{Q_{EE,spotř}}{m_W}$ [MJ/kg$_W$]

(5.4)

Together with evaporation capacity is energy consumption the main rating factor of drying process. Energy consumption is the amount of energy needed to evaporate 1 kg of water from material. Each experiment used constant parameters of drying medium (steam). Steam parameters were obtained from software tables X Steam 2.6 for certain enthalpy of steam and evaporated water. General formula (5.4) has been modified in order to application at performed experiments.

$$Q = \frac{(h_{tp} - h_{kon}) * m_{kon}}{m_W} \text{ [MJ/kg}_W\text{]} \quad (5.5)$$

where h_{tp} is enthalpy of steam, h_{kon} enthalpy of condensate water, m_{kon} amount of condensate water and m_W amount of evaporated water. By this progress energy consumption values were obtained for each experiment. Determined values were compared with theoretical values of energy consumption. Theoretical value of energy consumption is based on assumption of input materials temperature at 20°C and the use of specific phase heat at boiling temperature $\boldsymbol{l_v = 2,257\ [MJ/kg]}$ and specific heat capacity of water $\boldsymbol{c_p = 4200\ [J/kg \cdot K]}$ and wood matter $\boldsymbol{c_p = 1200\ [J/kg \cdot K]}$**.** The result is theoretical value of energy consumption needed to evaporate 1 kg of water $\boldsymbol{Q = 2,797}$ **[MJ].** As it is mentioned this value is theoretical, it doesn't cover the losses of drying process.

Values of energy consumption are in range of $\mathbf{Q = 3 - 3,5}$ $[\mathbf{MJ}]$**.** The favorable energy consumption value is at experiment no.6. Specifically, $\mathbf{Q = 3}$ $[\mathbf{MJ}]$. This value could be improved by optimization of process or dryer insulation improvement. For future design of dryer, the value of experiment no.5. will be used $\mathbf{Q = 3,43}$ $[\mathbf{MJ}]$**.**

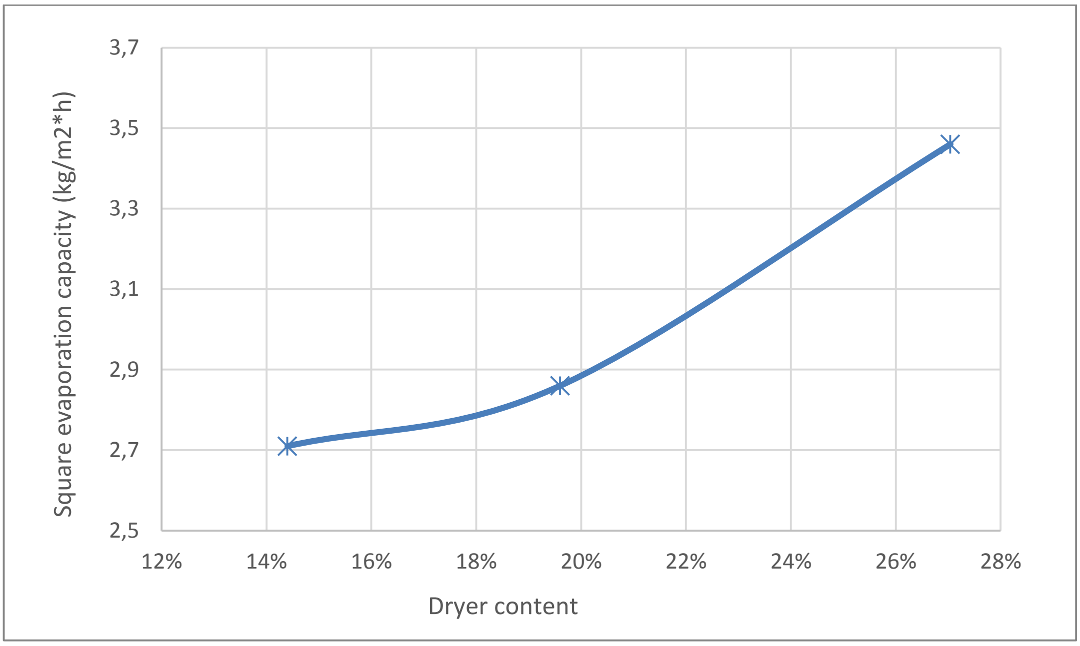
5.4 The evaluation of the experiments and the determining of all operational characteristics

The objective of all the experiments was to determine the operational characteristics of the dryer. In particular the square and the volumetric evaporation capacity, which are used in the design of a dryer. These experiments also enabled to a better understanding of the drying process.

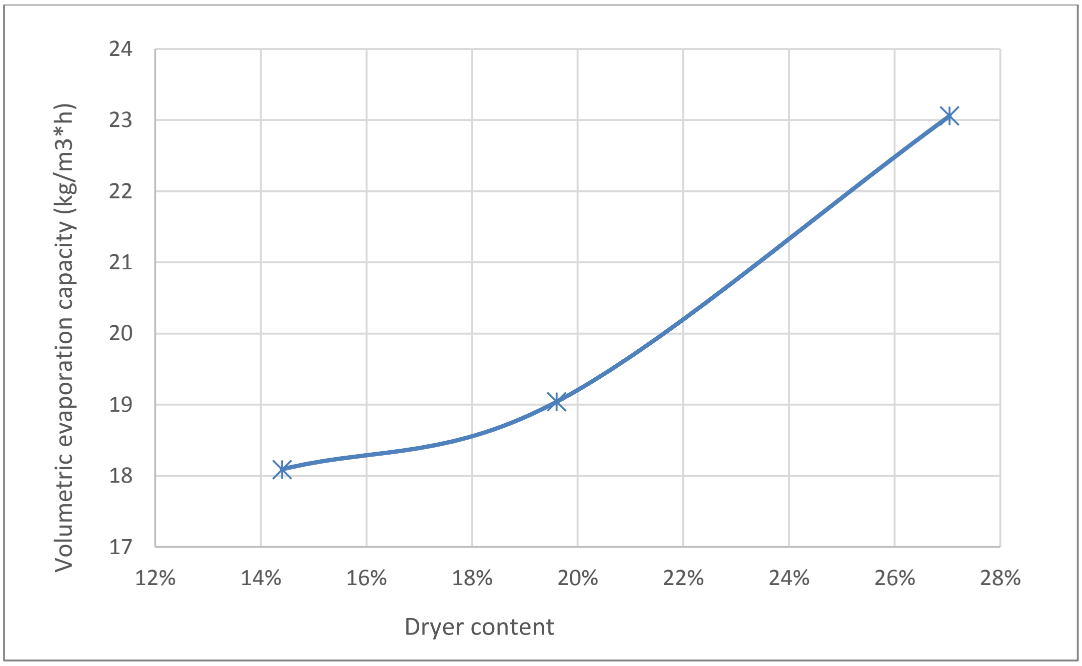
The experiment no.5 has shown that it is the most effective in the final evaluation of all the experiments. This conclusion is based on the above evaluation of each parameter. For this experiment, the dryer contained 27,4% of filling material. The dryer rotations were 2,9 rot/min. For experiment no.6 rotation was decreased, which had a positive impact on energy consumption. However the experiment no.5 achieved higher values of the square and volumetric evaporation capacity.

The operator can control the duration of drying and the percentage of content for the drying. These parameters were varied for each experiment, so that it is possible to graphically show the correlation of each operational characteristics and operational parameters.

Graph 5.1 *Square evaporation capacity – Drum filling*



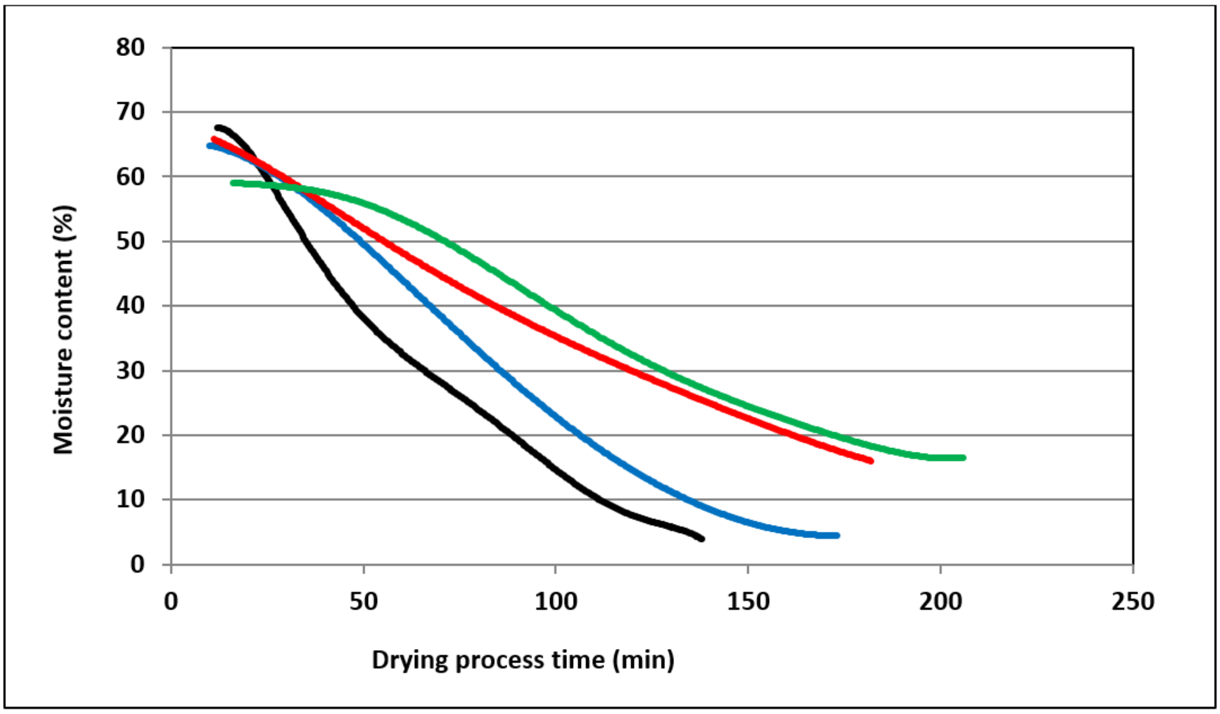
Graph 5.2 *Volumetric evaporation capacity – Drum filling*



From the previous graphs it is obvious that, even simple changes of basic operational parameters (dryer rotation, dryer content, drying time) will improve operational characteristic values. The energy consumption of drying is also a very important characteristic.

5.5 Drying curves of experiments

Graph 5.3 *Drying curves of experiments*



The drying curve describes the correlation of moisture content and the time of the drying process. For this thesis the drying curves were obtained from the recorded output container weights (par. 5.2) along with the time duration of drying process. As long as the input and output moisture of material values were known, it was possible to calculate the above graph.

6 A design of the dryer for biomass with high water content and evaluation of its operating balance

This chapter is focused on fuel consumption determination of two boiler operation system options. In the first option a given boiler combusting biomass with moisture content 20% and in the second a biomass dryer is integrated before the boiler and the waste biomass with moisture content of 60% is dried to moisture content of 20%. The fuel consumption difference is furher used for economical evaluation. Drying device design is based on determined consumption and experimentaly obtained operational characteristics. Designed device is afterwards economically evaluated.

6.1 The determination of fuel consumption in boiler with moisture content of 20%

Designed dryer will be used for pre-treatment of the fuel before its combusting in given boiler. In the first step it is necessary to determine fuel consumption of the fuel in boiler. Based on fuel consumption value, dryer can be designed.

Input data – fuel properties

Input data represents properties of the used fuel. They were given by the assignment. The fuel is biomass (wood chips) with following properties

- The gross calorific value $Q_s = 19769\ kJ \cdot kg^{-1}$
- Moisture content $W = 20\ \%$
- Ash in dry matter $A^d = 1{,}61\ \%$
- Carbon in dry matter $C^{daf} = 50{,}9\ \%$
- Hydrogen in dry matter $H^{daf} = 6{,}93\ \%$
- Nitrogen in dry matter $N^{daf} = 0{,}26\ \%$
- Sulfur in combustible $S^{daf} = 0{,}003\%$
- Oxygen in combustible $O^{daf} = 41{,}8\ \%$

Fuel properties conversion

Table 6.1 *Fuel composition*

Fuel composition	Value	Symbol	Unit
Moisture content	0,2	W	-
Ash in combustible	0,016159	A	-
Carbon in combustible	0,50959	C	-
Hydrogen in combustible	0,069334	H	-
Nitrogen in combustible	0,002646	N	-
Sulfur in combustible	0,0000331	S	-
Oxygen in combustible	0,418397	O	-
The gross calorific value	19769	Qs	$kJ\cdot kg^{-1}$

Mass fraction of fuel:

$$h + A + W = 1 \rightarrow 0{,}7831 + 0{,}0161 + 0{,}2 = 1 \quad (6.1)$$

Fuel composition in its intial state:

$$A^r = A^d \cdot (1 - W^r) = 0{,}016159 \cdot (1 - 0{,}2) = 0{,}0129[-] \quad (6.2)$$

$$C^r = C^{daf} \cdot (1 - A^r - W^r) = 0{,}50959 \cdot (1 - 0{,}0129 - 0{,}2) = 0{,}4011[-] \quad (6.3)$$

$$H^r = H^{daf} \cdot (1 - A^r - W^r) = 0{,}069334 \cdot (1 - 0{,}0129 - 0{,}2) = 0{,}0546[-] \quad (6.4)$$

$$S^r = S^{daf} \cdot (1 - A^r - W^r) = 0{,}0000331 \cdot (1 - 0{,}0129 - 0{,}2) = 0{,}00002[-] \quad (6.6)$$

$$N^r = N^{daf} \cdot (1 - A^r - W^r) = 0{,}002646 \cdot (1 - 0{,}0129 - 0{,}2) = 0{,}0021[-] \quad (6.7)$$

$$O^r = O^{daf} \cdot (1 - A^r - W^r) = 0{,}418397 \cdot (1 - 0{,}0129 - 0{,}2) = 0{,}3239[-] \quad (6.8)$$

The gross calorific value of fuel in its initial state:

$$Q_s^r = Q_s^{daf} \cdot (1 - A^r - W^r) = 19769 \cdot (1 - 0{,}0161 - 0{,}2) = 15559 \left[\frac{kJ}{kg}\right] \quad (6.9)$$

Calorific value of fuel in its initial state:

$$Q_i^r = Q_s^r - 2453 \cdot (W^r + 9 \cdot H^r) = 15559{,}64 - 2453 \cdot (0{,}2 + 9 \cdot 0{,}0546) = 13872{,}31 \left[\frac{kJ}{kg}\right] \quad (6.10)$$

6.2 Stoichiometric calculation

The minimum oxygen volume required for ideal combustion of 1kg of fuel:

$$O_{O_2min} = 22{,}39 \cdot \left(\frac{C^r}{12{,}01} + \frac{H^r}{4{,}032} + \frac{S^r_{prch}}{32{,}06} - \frac{O^r}{32}\right) = 22{,}39 \cdot \left(\frac{0{,}40108}{12{,}01} + \frac{0{,}0545}{4{,}032} + \frac{0{,}00002}{32{,}06} - \frac{0{,}3293}{32}\right) = 0{,}8204 \left[\frac{Nm^3}{kg}\right] \quad (6.11)$$

The minimum dry air volume required for ideal combustion of 1kg of fuel:

$$O_{VSmin} = \frac{O_{O_2min}}{0{,}21} = \frac{0{,}8204}{0{,}21} = 3{,}9065 \left[\frac{Nm^3}{kg}\right] \quad (6.12)$$

The minimum moist air volume required for ideal combustion of 1kg of fuel:

$$O_{VVmin} = x_v \cdot O_{VSmin} = 1{,}016 \cdot 3{,}9065 = 3{,}969 \left[\frac{Nm^3}{kg}\right] \quad (6.13)$$

Volume of water vapor in this volume:

$$O^V_{H_2O} = O_{VVmin} - O_{VSmin} = (x_v - 1) \cdot O_{VSmin} = 3{,}969 - 3{,}9065$$

$$O^V_{H_2O} = 0{,}0625 \left[\frac{Nm^3}{kg}\right] \quad (6.14)$$

Partial volumes of flue gases segments produced by combustion of solid fuels with air excess α=1,5

The volume of carbon dioxide:

$$O_{CO_2} = \frac{22{,}26}{12{,}01} \cdot C^r + 0{,}0003 \cdot O_{VSmin} = \frac{22{,}26}{12{,}01} \cdot 0{,}401 + 0{,}0003 \cdot 3{,}9065 = 0{,}7446 \left[\frac{Nm^3}{kg}\right] \quad (6.15)$$

The volume of sulfur dioxide:

$$O_{SO_2} = \frac{21{,}89}{32{,}06} \cdot S^r = \frac{21{,}89}{32{,}06} \cdot 0{,}00002 = 0{,}000018 \left[\frac{Nm^3}{kg}\right] \quad (6.16)$$

The volume of nitrogen:

$$O_{N_2} = \frac{22{,}4}{28{,}016} \cdot N^r + 0{,}7805 \cdot O_{VSmin} = \frac{22{,}4}{28{,}016} \cdot 0{,}00208 + 0{,}7805 \cdot 3{,}9065 = 3{,}0507 \left[\frac{Nm^3}{kg}\right] \quad (6.17)$$

The Argon volume, which includes other rare gases in the air:

$$O_{Ar} = 0{,}0092 \cdot O_{VSmin} = 0{,}0092 \cdot 3{,}9065 = 0{,}0359 \left[\frac{Nm^3}{kg}\right] \quad (6.18)$$

The volume of dry flue gases:

$$O_{SSmin} = O_{CO_2} + O_{SO_2} + O_{N_2} + O_{Ar} = 0{,}7446 + 0{,}000018 + 3{,}0507 + 0{,}0359 = 3{,}8312 \left[\frac{Nm^3}{kg}\right] \quad (6.19)$$

The volume of water vapor in minimum volume of moist flue gases:

$$O_{H_2O}^{S} = \frac{44{,}8}{4{,}032} \cdot H^r + \frac{22{,}4}{18{,}016} \cdot W^r + O_{H_2O}^{V} = \frac{44{,}8}{4{,}032} \cdot 0{,}0545 + \frac{22{,}4}{18{,}016} \cdot 0{,}2 + 0{,}0625 = 0{,}9175 \left[\frac{Nm^3}{kg}\right] \quad (6.20)$$

Minimum volume of moist flue gases:

$$O_{SVmin} = O_{SSmin} + O_{H_2O}^{S} = 3{,}8312 + 0{,}9175 = 4{,}7371 \left[\frac{Nm^3}{kg}\right] \quad (6.21)$$

The flue gases volume produced by combusting of 1 kg of fuel with air excess $\alpha > 1$:

$$O_{SV} = O_{SVmin} + (\alpha - 1) \cdot O_{VVmin} = 4{,}7371 + (1{,}5 - 1) \cdot 3{,}969 = 6{,}7332 \left[\frac{Nm^3}{kg}\right] \quad (6.22)$$

The real flue gases volume:

$$O_{SV}^{t_s,p_s} = O_{SV} \cdot \frac{273+t_s}{273} \cdot \frac{0{,}1013}{p_s} = 6{,}7332 \cdot \frac{273+150}{273} \cdot \frac{0{,}1013}{0{,}1013} = 10{,}432 \left[\frac{m^3}{kg}\right] \quad (6.23)$$

The flue gases enthalpy determination with air excess $\alpha > 1$

This simplified determination is based on temperature behind the boiler (based on references and consultation temperature of 150°C is choosed). The enthalpy determination was performed by regression growth of enthalpy of each flue gas segment. Those were obtained from PC software Excel.

Table of specific flue gas segment enthalpies refers to biomass and maximum temperature 2500°C, each segment regression formula reading and each segment enthalpy determination is not included in this calculation.

The stoichiometric flue gases enthalpies determination, $\alpha = 1{,}5$:

$$h_{Smin}^{t} = O_{CO_2} \cdot h_{CO_2}^{t} + O_{SO_2} \cdot h_{SO_2}^{t} + O_{N_2} \cdot h_{N_2}^{t} + O_{Ar} \cdot h_{Ar}^{t} + O_{H_2O} \cdot h_{H_2O}^{t} + O_{O_2} \cdot h_{O_2}^{t} + a_{ú} \cdot A^r \cdot h_{pop}^{t} = 0{,}7446 \cdot 261{,}7015 + 0{,}00002 \cdot 290{,}9340 + 3{,}0507 \cdot 194{,}4998 + 0{,}0359 \cdot 139{,}5522 + 0{,}0509 \cdot 226{,}8007 + 0{,}8204 \cdot 198{,}7988 + 0{,}2 \cdot 0{,}0129 \cdot 124{,}1715 = 968{,}18 \left[\frac{kJ}{kg}\right] \quad (6.24)$$

The determination of enthalpy of minimum required amount of air at 150°C

$$h_{Vmin}^{t} = O_{VSmin} \cdot h_{VS}^{t} + O_{H_2O}^{V} \cdot h_{H_2O}^{t} = 3{,}9065 \cdot 199{,}0552 + 0{,}0625 \cdot 226{,}8007 = 791{,}794 \left[\frac{kJ}{kg}\right] \quad (6.25)$$

The flue gases enthalpy determination with air excess α = 1,5 and at the temperature 150°C

$$h_S^{t,\alpha} = h_{Smin}^t + (\alpha - 1) \cdot h_{Vmin}^t = 1001{,}81 + (1{,}5 - 1) \cdot 791{,}794 = 1397{,}71 \left[\frac{kJ}{kg}\right] \quad (6.26)$$

6.3 Boiler efficiency determination with air excess α = 1,5

The overall boiler efficiency is calculated from specific boiler losses as

$$\eta_k = 1 - z_c - z_{co} - z_{sv} - z_f - z_k$$

Where: z_c – overall unburnt losses

z_{co} – loss due to carbon monoxide

z_{sv} – loss due to surface radiation

z_f – loss due to heat of solid residues

z_k – stack loss

Overall unburnt losses:

Overall unburt losses are calculated from partial unburnt losses

$$z_c = z_{cs} + z_{cú} + z_{cr}$$

Partial unburnt losses calculation:

Unburnt losses in bottom ash - slag:

$$z_{cs} = \frac{C_S}{1-C_S} \cdot X_S \cdot \frac{A^r}{Q_{i\,red}} \cdot Q_{ci} = \frac{0{,}09}{1-0{,}16} \cdot 0{,}62 \cdot \frac{0{,}0129}{14072{,}11} \cdot 32600 = 0{,}00185[-] \quad (6.27)$$

Unburnt losses in fly ash:

$$z_{cú} = \frac{C_ú}{1-C_ú} \cdot X_ú \cdot \frac{A^r}{Q_{i\,red}} \cdot Q_{ci} = \frac{0{,}2}{1-0{,}2} \cdot 0{,}27 \cdot \frac{0{,}0129}{14072{,}11} \cdot 32600 = 0{,}00204[-] \quad (6.28)$$

Unburnt losses in bottom ash - throughs:

$$z_{cr} = \frac{C_r}{1 - C_r} \cdot X_r \cdot \frac{A^r}{Q_{i\,red}} \cdot Q_{ci} = \frac{0{,}3}{1 - 0{,}3} \cdot 0{,}06 \cdot \frac{0{,}0129}{14072{,}11} \cdot 32600 = 0{,}000778[-]$$

Coefficients used in previous calculation C_i a X_i (the portion of ash in slag, throughs and fly) they were obtained from reference [1]. Specifically: Cs=0,09; Cr=0,2; Cú=0,3; Xs=0,62; Xr=0,06; Xú=0,27 (6.29)

$$z_c = 0{,}00185 + 0{,}00204 + 0{,}000778 = 0{,}004678[-] \quad (6.30)$$

Loss due to carbon monoxide

$$Z_{CO} = \frac{0{,}2116 \cdot mgCO \cdot O_{SS\min}}{(21 - O_{O2ref}) \cdot Q_i} = \frac{0{,}2116 \cdot 650 \cdot 3{,}83}{(21 - 0{,}11) \cdot 13872{,}31} = 0{,}0018 \qquad (6.31)$$

Loss due to surface radiation

$$Z_{sv} = 0{,}01[-] \qquad (6.32)$$

Choosed from reference [1]

Loss due to heat in solid residues:

Overall loss due to heat in solid residues is calculated from partial calculations:

$$z_f = z_{fs} + z_{fú} + z_{fr}$$

Partial calculations:

Loss due to heat in solid residues in bottom ash - slag

$$z_{fs} = \frac{X_s}{1 - C_s} \cdot \frac{A^r}{Q_{i\,red}} \cdot C_p \cdot t_p = \frac{0{,}62}{1 - 0{,}09} \cdot \frac{0{,}0129}{14072{,}11} \cdot 10{,}8726 \cdot 600 = 0{,}00034[-] \qquad (6.33)$$

Loss due to heat in solid residues in bottom ash - throughs

$$z_{fr} = \frac{X_r}{1 - C_r} \cdot \frac{A^r}{Q_{i\,red}} \cdot C_p \cdot t_p = \frac{0{,}27}{1 - 0{,}2} \cdot \frac{0{,}0129}{14072{,}11} \cdot 10{,}8726 \cdot 600 = 0{,}0000439[-] \qquad (6.34)$$

Loss due to heat in solid residues in fly ash

$$z_{fú} = \frac{X_ú}{1 - C_ú} \cdot \frac{A^r}{Q_{i\,red}} \cdot C_p \cdot t_p = \frac{0{,}06}{1 - 0{,}3} \cdot \frac{0{,}0129}{14072{,}11} \cdot 10{,}8726 \cdot 600 = 0{,}000173[-] \qquad (6.35)$$

Coefficients used in previous calculations C_i a X_i, have same values as in calculation of unburnt losses.

$$z_f = z_{fs} + z_{fr} + z_{fú} = 0{,}0005662[-] \qquad (6.36)$$

Stack loss

$$z_k = (1 - z_c) \cdot \frac{I_S^{t_k,\alpha_k} - I_S^{t_{vz},\alpha_k}}{Q_{i\,red}} = (1 - 0{,}0046) \cdot \frac{1397{,}71 - 231{,}1}{14072{,}11} = 0{,}0825[-] \qquad (6.37)$$

Overall boiler efficiency

$$\eta_k = 1 - z_c - z_{co} - z_{sv} - z_f - z_k$$

$$\eta_k = 1 - 0{,}0046 - 0{,}0018 - 0{,}01 - 0{,}0005 - 0{,}0825 = 0{,}9004[-] \quad \rightarrow 90\% \tag{6.38}$$

6.4 Fuel consumption determination

Flue gases enthalpies refers to 1 kg of fuel. Following step will lead to fuel consumption determination, required for boiler operation.

Nominal power of steam boiler:

$$M_p = 1MW \tag{6.39}$$

Fuel consumption:

$$M_{sp} = \frac{Q_V}{Q_{i\,red} \cdot \eta_k} = \frac{1000}{14072{,}11 \cdot 0{,}9004} = 0{,}07892 \left[\frac{kg}{s}\right] = \mathbf{284{,}12} \left[\frac{kg}{h}\right] \tag{6.40}$$

6.5 Comparison of fuel consumption calculation with different moisture content

This chapter states organized comparison of boilers operation with different fuel moisture options. It is comparison of fuel consumption in boiler with nominal power of 1MW. The main difference is in fuel properties. In first case is used fuel with moisture content 60% unlike second case where fuel has moisture content 20%.

Table 6.2 *Fuel consumption calculations comparison*

Fuel composition			
Moisture content		**60 %**	**20 %**
A^r		0,006464	0,012927
C^r		0,200542	0,401084
H^r		0,027285	0,054571
S^r		1,3E-05	2,61E-05
N^r		0,001041	0,002083
O^r		0,164654	0,329309
Q_s^r	[kJ·kg^{-1}]	**7779**	**15559**
Q_i^r	[kJ·kg^{-1}]	**5705**	**13864**
Stoichimetry and enthalpy calculation			
O_{O_2min}	[Nm3/kg]	0,41	0,82
O_{VSmin}	[Nm3/kg]	1,95	3,91
O_{VVmin}	[Nm3/kg]	1,98	3,97
$O_{H_2O}^V$	[Nm3/kg]	0,0312	0,062
$h_S^{t,\alpha}$	[kJ/kg]	839	1397
h_{Vmin}^t	[kJ/kg]	139	231
Final results			
Boiler power [MW]		1	1
Fuel calorific value [kJ/kg]		5787	14072
Stack loss [-]		0,12	0,082
Boiler overall efficiency [%]		83,4	90
Fuel consumption [kg/h]		**746**	**284**

Previously mentioned comparison proves ineffective boiler operation when combusted fuel contains 60% of moisture. Therefore, drying of fuel as a pre-treatment is important before its combusting.

6.6 Operational balance of drying

Fuel consumption of given boiler was determined by previous calculation. Based this value, drying balance can be calculated. Requirement for steam drum dryer is to dry material (wood chips) from input moisture 60% to output moisture 20% and output flow rate 284 kg/hr. This is fuel flow rate required by given boiler with nominal power 1 MW and overall efficiency 90 %

Input moisture content of material:

$$w_r = 0{,}6\ [-] \tag{6.41}$$

Output moisture content of material:

$$w_{r1} = 0{,}2\ [-] \tag{6.42}$$

Required output flow rate of material:

$$m_{pal} = 284\ [kg/hod] \tag{6.43}$$

Water amount in output material:

$$m_{2W} = m_{pal} * w_{r1}\ \left[\frac{kg}{hod}\right] \tag{6.44}$$

$$m_{2W} = 284{,}12 * 0{,}2 = 56{,}8\ [kg/hod] \tag{6.45}$$

Amount of dry matter:

$$m_{2A} = m_{pal} * (1 - w_{r1})\ \left[\frac{kg}{hod}\right] \tag{6.46}$$

$$m_{2A} = 284{,}12 * (1 - 0{,}2) = 227\ [kg/hod] \tag{6.47}$$

Required input flow rate of material:

$$m_{1A} = m_{pal} * \left(\frac{1-w_{r1}}{1-w_r}\right)\ \left[\frac{kg}{hod}\right] \tag{6.48}$$

$$m_{1A} = 284{,}12 * \left(\frac{1-0{,}2}{1-0{,}6}\right) = 568\ [kg/hod] \tag{6.49}$$

Amount of water in input material:

$$m_{1W} = m_{1A} * 0{,}6\ \left[\frac{kg}{hod}\right] \tag{6.50}$$

$$m_{1W} = 586{,}56 * 0{,}6 = 340\ \left[\frac{kg}{hod}\right] \tag{6.51}$$

Amount of evaporated water:

$$m_W = m_{1A} - m_{pal} \left[\frac{kg}{hod}\right] \quad (6.52)$$

$$m_W = 568{,}24 - 284{,}12 = 284 \left[\frac{kg}{hod}\right] \quad (6.53)$$

The determination of required amount of steam for drying process

Calculation of required amount of steam for drying process uses experimentally obtained value of energy consumption and previously determined amount of evaporated water during drying process.

Total amount of heat energy required for drying process:

$$Q_c = Q_{ohv} + m_w = 3{,}43 \cdot 284{,}1 = 974{,}4\ MJ = 270\ kW \quad (6.54)$$

Total amount of steam required for drying process:

$$m_{steam} = \frac{270}{2257} = 0{,}119 \frac{kg}{s} = 432 \frac{kg}{h} \quad (6.55)$$

Assumed latent heat of water r_{FG} = 2257 kJ/kg.

Table 6.3 *Drying process balance*

Input moisture content	w_r	0,6	[−]
Output moisture content	w_{r1}	0,2	[−]
Required output flow rate of material	$\boldsymbol{m_{pal}}$	**284**	**kg/hr**
Amount of water in output material	m_{2W}	56,8	kg/hr
Amount of dry matter	m_{2A}	227	kg/hr
Required input flow rate of material	$\boldsymbol{m_{1A}}$	**568**	**kg/hr**
Amount of water in output material	m_{1W}	340	kg/hr
Amount of evaporated water	m_W	284	kg/hr

6.7 The dryer sizes determination

Dryer dimension calculation is using experimentally obtained evaporation capacity. Specifically, it is square and volumetric evaporation capacity

Table 6.4 *Dryer design auxiliary coefficients*

Square evaporation capacity	o_S	2,17	$[kg/m^2 \cdot h]$
Volumetric evaporation capacity	o_V	22,8	$[kg/m^3 \cdot h]$

Drum volume

$$V = \frac{m_w}{o_V}\ [m^3] \tag{6.56}$$

$$V = \frac{284{,}12}{22{,}87} = 12{,}4[m^3] \tag{6.57}$$

Drum volume is determined by amount of evaporated water and specific volume evaporativity ration. Drum volume value states general concept of drying device size.

Area of drum heated surface

$$S = \frac{m_w}{o_S}\ [m^2] \tag{6.58}$$

$$S = \frac{284{,}12}{3{,}46} = 131\ [m^2] \tag{6.59}$$

In contrast to drum volume, the value of drum heated surface is important design parameter, which states exact requirement for heated surface area in dryer. This surface will be mostly consist of pipes in purposed dryer, however more surface elements with different shape can be used, to maximize heat transfer.

Drum diameter

$$d = \sqrt[3]{\frac{V}{\pi}} = \sqrt[3]{\frac{12{,}42}{\pi}} = 1{,}58\ m \tag{6.60}$$

Drum length

$$l = 4 \cdot d = 4 \cdot 1{,}58 = 6{,}32\ m \tag{6.61}$$

The values of drums diameter and length coming from drum volume. These values are determined in order to dryer be able to construct.

The resulting shape of the dryer based on the previous calculations is a main rotating drum with a diameter 1,58 m and length 6,32 m. The drying chamber inside of the drum consists of piping and geometrical plates, these are used as a heating surface. Drying the chamber is covered with a heat insulation material. The outer surface of the drum is made from metal plates. The rotational movement of the drum is secured by bearing houses. Propulsion of this rotational movement is by electromotors. Input and output of the material is by scroll feeders. The base of dryer is made from I-shape beams, this will ensures the rigidity of the machine.

6.8 Estimation of the investment cost of a dryer

It is not possible on this design to obtain a quote from a manufacturer or catalogue. The available dryers are constructed by specialist firms as a one of production. Based on this fact, it is clearly very difficult to estimate the cost of a dryer. The overall cost of this investment is calculated from material costs and costings of each component. The material estimation is based on a 3D model of a dryer made by Auto-CAD software. This software enables the calculation of the approximate amount of materials used for a dryer construction.

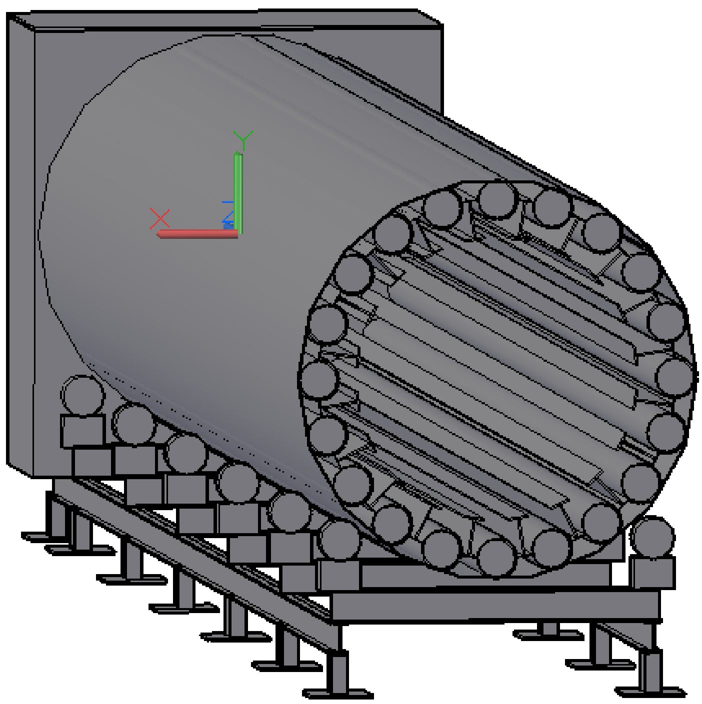


Figure 6.1 *Purposed dryer*

```
 ----------------    SOLIDS    ----------------
Mass:                    606506048.1756
Volume:                  606506048.1756
Bounding box:         X: -1020.0000  --  1020.0000
                      Y: -1580.0000  --  1020.0000
                      Z: -10070.0000  --  1070.0000
Centroid:             X: -143.1965
                      Y: 131.1755
```

Figure 6.2 *Geometrical data of purposed dryer*

The overall weight of dryer is only an approximate value. This value was obtained from the dryer´s 3D model made by Auto-CAD software. The dryer investment cost is based on the above value.

Table 6.5 *The amount of material for a purpose dryer*

Construction volume (m^3)	Material type	Steel density (kg/m^3)	Total weight (kg)
0,61	11 343	7850	4757

Because each dryer is a one off production it is difficult to estimate the cost. The cost of a dryer based on the consultation with thesis supervisor is approx. 2,5 mil.CZK

Table 6.6 *The Investment cost of a dryer*

Item	Cost (CZK)
Components – electromotors, bearing houses, screw feeder	100 000
Material (price per unit 150 CZK/kg)–*rounded up*	800 000
Estimated price of manufacturing *	1 600 000
Total	2 500 000

**Estimated price covers, construction work, control system, reduction fittings, delivery and connection service.*

Three SIEMENS electromotors 1LA7 038-2AA1 are used as a propulsion of rotational movement. Price and detail information were obtained at following websites: http://www.elektromotory-siemens.cz/obchod/elekromotory-siemens-rady-1la7/elektromotor-siemens-1la7-083-2aa1-1-1kw.html

The bearing houses ensure drums placing and its rotating movement, 24 of these bearing houses are used in purposed dryer construction. Price and detail information were obtained at following websites: http://eshop.exvalos.cz/cs/loziskove-domecky-y-a-loziska/14908-sy-17-tf-skf.html

The scroll feeder is used for delivery of material into the drying chamber. The diameter of this feeder is 250mm. Price and detail information were obtained at following websites: http://www.filtrzeos.cz/

When the material unit price = 150 CZK/kg is assumed and the overall weight of a dryer is 4757 kg, the investment cost of material is 713 500 CZK, the safety round is 800 000 CZK. The manufacturing costs are relatively high due to complicated specialist manufacturing. It is necessary to consider other expenses, such as steam piping, delivery and connection service. A financial reserve is included in the estimated price of manufacturing at 1 600 000 CZK.

7 The economic evaluation of the use and purpose of a dryer

The evaluation of projects economical effectiveness, is being performed as a project preparation phase. The task of this evaluation is to provide all necessary information, which is used for project implementation decision. The large scale of necessary actions is needed for this kind of evaluation:

- Getting of input data
    - Investment cost of device
    - Operational balance
- The conversion of technical parameters into financial cost
- The choice of evaluation methodology
- The calculation of economical evaluation criteria
- "What – if" and risk analysis
- Conclusion

The economical evaluation of this project is based on two option of boiler operation. In the first option, the boiler is combusting a fuel without any pre-treatment, unlike second option, where the boiler combusting a fuel which has been dried. Therefore, it is very important to evaluate if the profit and payback will be ensured by lower fuel price, with 60% of moisture content. From the perspective of the economical evaluation requirements is the price of fuel (wood chips) the key parameter. In Czech Republic area there are many (wood chips) suppliers. Obviously, every supplier offers wood chips for different price. Therefore, as a part of the economical evaluation is a survey of wood chips price. Data obtained by this survey are mentioned in following Table 7.1.

Table 7.1 *Wood chips prices overview*

Supplier	Price (CZK/t)	Price (CZK/GJ)
DREPOS s.r.o.	1670	165
Rioni	1956	193
Pavel Kisling	667	66
Lesy města Brna	1907	189
JSR s.r.o.	978	97
Kutnohorské Lesy	1000	99

The calorific value Qir = 10,1 MJ/kg applies to all items.

The prices mentioned in previous Table 7.1 were obtained from TZB-info.cz database. Due to objectivity of this economical evaluation, other survey of wood chips prices was performed, based on consultation directly with suppliers.

Table 7.2 *Wood chips prices overview*

Supplier	Price (CZK)	Unit	Price (CZK/GJ)
Lesy hl. města Prahy	400	PRMS	175
Technické služby Bystřice p.H.	290	PRMS	133
ZDO - Kralupy n. V.	400	PRMS	175
ZDEMAR – Ústí n. L.	400	PRMS	175
Obec - Potštejn	1,4	kg	139
Andrla s.r.o.	1,8	kg	178
JILOS	480	PRMS	210

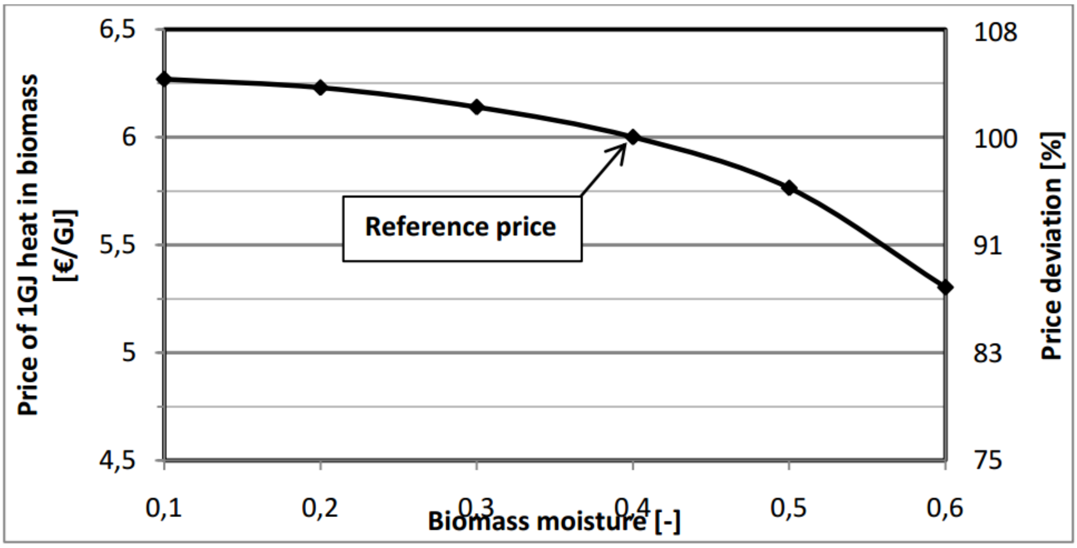
Necessary unit conversion was calculated by using following coefficients (assumptions).

Table 7.3 *Unit conversion*

Fuel	Cubic meter, loose matter	Cubic meter, full matter	Density (kg/PRMS)
Wood chips, loose	1	0,4	225

The supervisor of this thesis provided an article specialized on the impact of change of moisture content in biomass to its combustion properties and more importantly to its price. The reference price obtained from this article was used for economical evaluation.

Graph 7.1 *The dependence of moisture content and price of biomass*



The unit price of fuel (wood chips) with moisture content 20% is given by the assignment of this thesis. The unit price of wood chips with moisture content 60% was stated based on article provided by supervisor of this thesis and the survey of wood chips prices. Stated prices are mentioned in following table 7.4.

Table 7.4 *Stated unit prices of wood chips used in economical evaluation*

Moisture content	Price CZK/GJ	Price CZK/kg	Calorific value (MJ/kg)
60 %	130	0,74	5705
20 %	170	2,35	13864

7.1 Option 1: A boiler operation with dry fuel

Using a boiler operating with wood chips with a moisture content of 20%. The number of operational hours and the price of the fuel are used to evaluate this option. Values of these parameters were obtained based on consultation with the supervisor of this thesis. The fuel consumption, boilers efficiency and power are based on previous calculation.

Table 7.5 *Option 1 - Assignment*

Fuel consumption of boiler	**284**	**Kg/hours**
Calorific value of the fuel	13	MJ/kg
Price of the fuel (wood chips)	2,35	CZK/kg
Number of operational hours	5000	hr/year
Boiler efficiency	90	%
Boiler power	1	MW

The crietria for evaluation of Option 1

The evaluation criterion of the Option 1 is annual fuel cost. For this option it is only criteria that can be used, because the overall annual cost of this option is made by the fuel costs.

$$N_1 = N_{pal,1} = M_{sp} \cdot n_1 \cdot H$$

Where:

N_1 – overall annual cost of Option 1

$N_{pal,1}$ – annual fuel cost of Option 1

M_{sp} – fuel consumption of the boiler

n_1 – price of fuel (wood chips) with moisture content of 20%,

H – number of operation hours

Annual fuel costs (the option without drying of fuel)

$$N_{pal,1} = M_{sp} \cdot n_1 \cdot H = 284 \cdot 2{,}35 \cdot 5000 = 3338{,}4\ ths.CZK \quad (7.1)$$

$$\boldsymbol{N_1 = 3338{,}4\ ths.CZK}$$

7.2 Option 2: A boiler operation using a steam drum dryer

This option is a boiler operating with a dryer which drying wet fuel before its combusting. Drying of the fuel is provided by steam drum dryer. Fuel is dried from its raw state and a moisture content of 60% is reduced to a moisture content of 20%. The parameters used in the following calculations are based on identical references as in option 1.

Table 7.6 *Option 2 - Assignment*

Fuel consumption of boiler	**568**	**Kg/hr**
Calorific value of the fuel	13	MJ/kg
Price of the fuel (wood chips)	0,74	CZK/kg
Number of operational hours	5000	hr/year
Boiler efficiency	90	%
Boiler power	1	MW

The comparison between Option 1 and Option 2 is that the amount of fuel consumption is higher. This is soley due to the difference between in caloric values wet and dry fuel. So therefore a greater amount of fuel for drying with 60% of moisture content is needed to fulfill the requested amount of fuel consumption in boiler with moisture content of 20%

The cost of the wet wood chips is significantly lower than in Option 1. Obviously, the higher the content of moisture in the fuel the lower the price.

The crietria for evaluation of Option 2

The evaluation criteria of the Option 2 are annual fuel costs and operational cost. Operational costs cover dryer´s consumtion of electricity and steam.

$$N_2 = N_{pal,2} + N_{oper,el} + N_{oper,steam}$$

$$N_{pal,2} = M_{sp} \cdot n_2 \cdot H$$

$$N_{oper,el} = P_{el} \cdot n_{el} \cdot H$$

$$N_{oper,steam} = M_{sp} \cdot H \cdot Q_{od} \cdot n_{steam}$$

Where:

N_2 – overall annual cost of Option 2

$N_{pal,2}$ – annual fuel cost of Option 2

M_{sp} – fuel consumption of the boiler

n_2 – price of fuel (wood chips) with moisture content of 60%,

H – number of operation hours

P_{el} – total power of electricity consumers

n_{el} – electricity price per unit

n_{stean} – steam price per unit

Q_{od} – energy consumption of drying process

Annual fuel costs (the option with drying of the fuel)

$$N_{pal,2}=M_{sp} \cdot n_2 \cdot H = 568 \cdot 0{,}74 \cdot 5000 = 2102{,}4\ ths\ CZK \quad (7.2)$$

Operational costs

It is necessary to consider the electricity consumed by the electromotors and the amount of steam used in drying process as operational costs which are different for analysed cases, other operational costs are similar for both options.

The total power of electromotors used as a dryer rotation propulsion and scroll feeder is 10 kW. Unit price of electricity is considered 3,5 CZK/kWh

$$N_{oper,el}=P_{el} \cdot n_{el} \cdot H = 10 \cdot 3{,}5 \cdot 5000 = 175\ tis.Kč \quad (7.3)$$

The amount of steam used for drying process is calculated in chapter 6.11 – Balance of drying process calculation. The value of the amount of energy that is necessary to evaporate 1kg of water is used from the experiments 3,43 MJ. Steam that is produced by boiler is used for drying. Because the steam used by other machines can decrease, there is a sufficient amount of steam available which can be used for the drying process. Therefore, the price of this steam can be costed to the fuel used by the boiler.

$$n_{steam} = \frac{n_2}{0{,}9} = \frac{130}{0{,}9} = 144{,}4\ CZK/GJ$$

$$N_{oper,steam}=M_{sp} \cdot H \cdot Q_{od} \cdot n_{steam} = 274{,}12 \cdot 5000 \cdot 0{,}00343 \cdot 144{,}4 = 679\ ths.CZK \quad (7.4)$$

Overall annual costs of the Option 2

Unlike the annual costs in Option 1, the annual costs in this option contains additional operational costs generated by consumption of electricity and steam used in the drying process.

$$\boldsymbol{N_2 = 2102,4 + 175 + 679 = 2956,4\ ths.CZK}$$

Despite the increase of the overall annual costs caused by the operational costs, Option 2 is economically more favorable than Option 1, due to the significantly lower fuel costs.

7.3 Simple and discount payback

Simple and discount payback was calculated as a part of the economical evaluation. This calculation is based on the values of the annual costs of both options, and the dryer investment costs. Simple payback is expres as a proportion of the value of Option 1 and Option 2 annual costs difference and the value of dryer investment costs

Simple payback

$$T_s = \frac{IN}{CF} = \frac{IN}{N_{pal,1} - N_{var2}} = \frac{2500}{3338{,}4 - 2956{,}4} = \frac{2500}{382} = 6{,}5\ years \quad (7.6)$$

Discount payback

$$T_{ds} = \frac{IN}{DCF} = \frac{2500}{246,1} = 10,2\ years \quad (7.7)$$

Year	1	2	3	4	5	6	7	8	9	10	11
DCF	357	333	311	291	272	254	237	222	207	194	181
Total	357	690	1002	1293	1566	1820	2058	2281	2488	2683	2864

Discount payback consider the discount cash flow with discount coefficient 7%. The lifetime of dryer is 25 years.

The simple payback of purposed option is relatively positive. This is caused by significant decrease of fuel price. The boiler operational costs are identical for both options. However, Option 2 consider operational costs of drying. Those are electric energy and steam costs. Discount payback is higher than simple because of discount cash flow consideration.

Still, the discount payback is shorter than lifetime of dryer.

In term of economical evaluation objectivity, the "what-if" analysis was performed, to monitor behavior of payback in relation with dryer investment, operational hours and price of fuel.

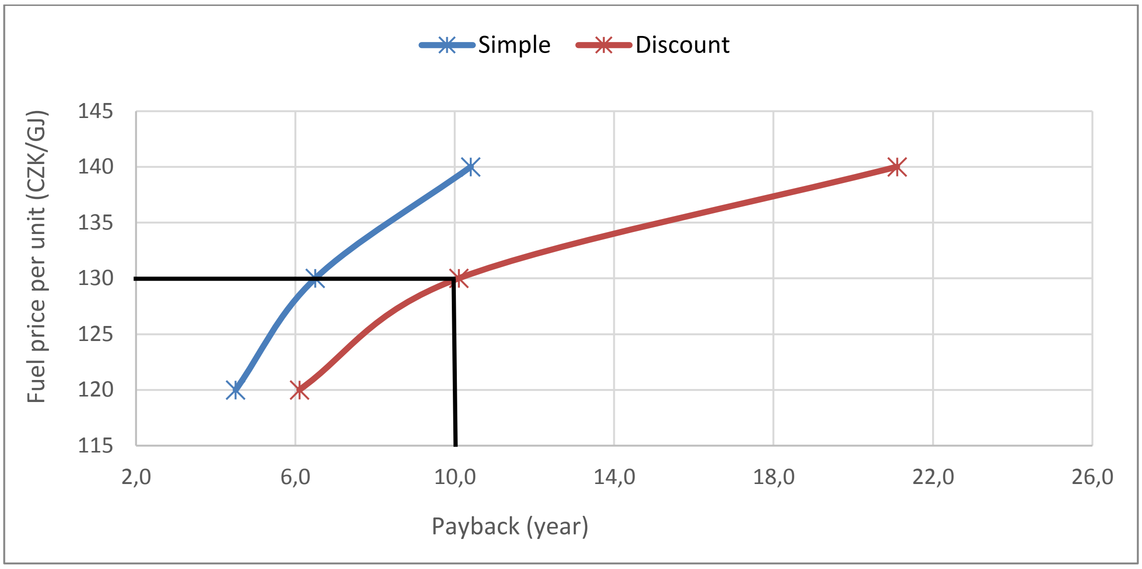
Table 7.7 *The "what if" analysis*

Investment (ths.CZK)	Payback (year)		Operational hours	Payback (year)		Fuel price (CZK/GJ)	Payback (year)	
	Simple	Disc.		Simple	Disc.		Simple	Disc
1500	3,9	8,5	6000	4	5,2	120	4,5	6,1
2500	6,5	10,2	5000	6,5	10,2	130	6,5	10,2
3500	9,2	12,2	4000	18,6	65,1	140	10,4	21,1

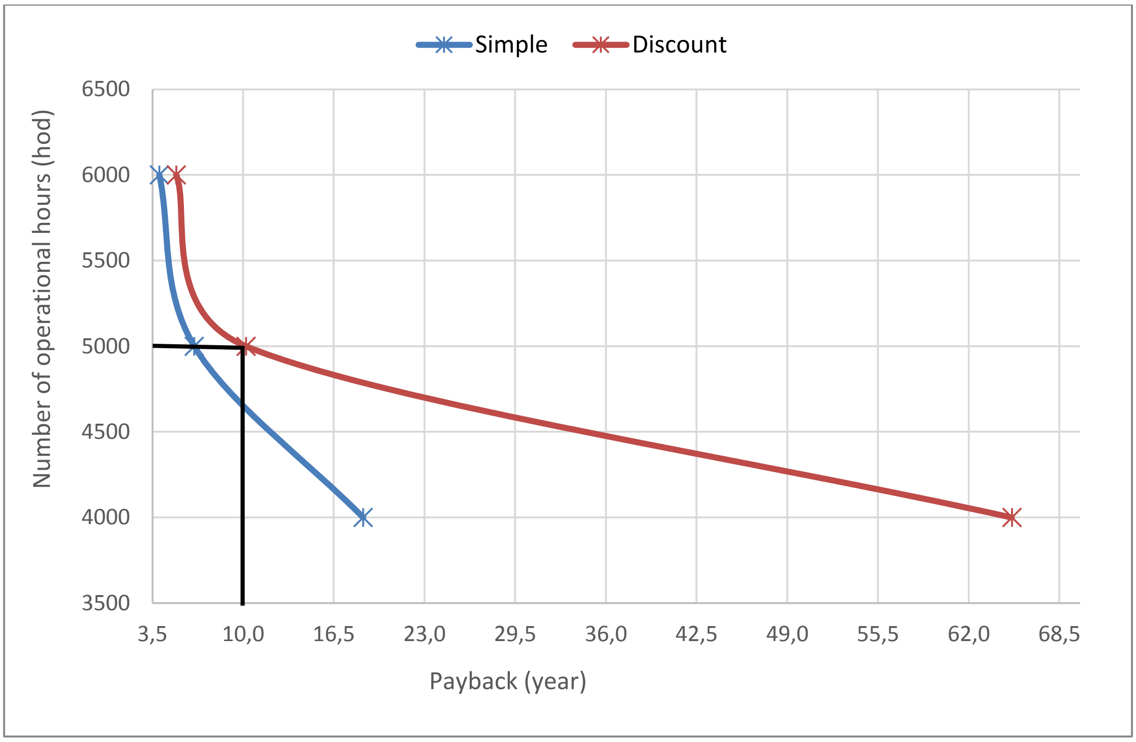
Fuel price per unit refers to fuel with 60% of moisture content.

The highest payback value is when the operational hours are lowest. Therefore, it is important to ensure maximal possible operational hours for this kind of device. Other relatively high payback value is when the price of fuel rises. The rise of this value is not as significant as in relation with operational hours, however the rise of fuel price can cause significant rise of payback value. The relation of payback and dryer investment cost doesn't show any significant rise. Based on presented analysis the economical evaluation is objective. The "what if" analysis is graphically shown in following graphs.

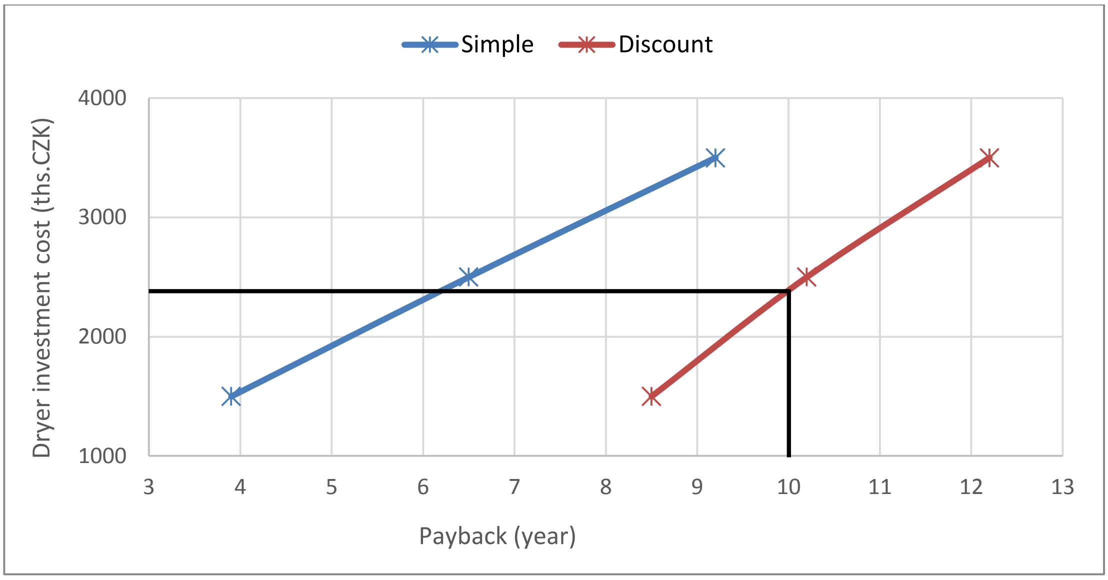
Graph 7.2 *Relation of payback and fuel price*



Graph 7.3 *Relation of payback and operational hours*



Graph 7.4 *Relation of payback and dryer investment cost*



The presented "what if" analysis proves significant change of payback when number of operational hours rise or decrease. Therefore, it is important to ensure maximal possible operational hours for this kind of device. Other relatively strong relation is between payback and the fuel price. The relation between payback and dryer investment cost it is not as strong as previous two. Thus, if the investment cost was estimated inaccurately, there is no high risk in the project realization.

If the requested payback period under 10 years is considered as economically acceptable, it is necessary to keep dryer investment cost, fuel price and number of operational hours at following values:

Fuel price per unit – 130 CZK/GJ

Number of operational hours – 5000 hours/year

Dryer investment cost – 2 400 000 CZK

7.4 The conclusion of the economical evaluation

The economical evaluation was arrived at after all the tasks of the thesis assignment had been achieved. This evaluation compares the two options of a boiler operation. In the first option, the boiler burning wood chips with **moisture content of 20%,** are purchased for a price **170 CZK/GJ.** In the second option wood chips are bought with a **moisture content of 60%** for a price of **130 CZK/GJ**. Once the wet wood chips are dried in the steam drum dryer they are then burnt in the boiler. The investment cost of a purpose dryer is **2 500 000 CZK.** The simple payback of this investment is **6.5 years.** This is based on the different fuel costs between option 1 and 2. The payback is positive, due to the high savings on fuel, and the steam is already in situ. Discount payback is **10 years**. This meets the given requirements. The project can now be viewed as economically viable.

Table 7.8 *Final economical evaluation*

	Fuel price (CZK/GJ)	Annual fuel costs (ths.CZK)	Savings (ths.CZK)	Investment (ths.CZK)	Payback (year)	
					Simple	Discount
Option 1	170	3 338	382	2500	6,5	10
Option 2	130	2 956				

8 Conclusion

The main task of this thesis was to design a biomass dryer. This dryer will be drying the fuel (wood chips) with high water content before burning in a given boiler. This thesis proves the suitability of drying fuel before it is burnt. The drying process allows the purchasing of wood chips with a high water content, for a significantly lower price. After drying, the wood chips become suitable fuel for a given boiler.

The drying of the fuel is highly suited to where is available steam produced by a boiler which can be used for drying purposes. The best type of dryer, that can be used for this project is steam drum dryer.

Multiple experiments were necessary to conduct as a part of design of the dryer. These experiments simulated drying process on a small scale. The experiments were conducted at CTU laboratories, where the steam drum dryer is an inclusive machine of the CTU laboratory equipment.

As a result of the evaluation of experiments, the operational characteristics parameters were obtained. **Square evaporation capacity: 2,17 kg/m^2·h, Volumetric evaporation capacity: 22,8 kg/m^3·h**

In chapter 6 of thesis, the boiler efficiency and fuel consumption in the boiler were calculated. The calculation used fuel with a moisture content of 20%. **The fuel consumption in the boiler with power 1 MW equals 284 kg/h.**

The drying process calculation required amounts of wet material and the volume of evaporated water given during drying process. By using these values, it was possible to calculate the dryer´s dimensions.

The dryer´s dimensions were established using the values of evaporation capacity determined from the experiments and the values of evaporated water during the drying process. The proportion of these two values determined the volume of the dryer´s drum and the area of drum´s heated surface. **The area of drum´s heated surface is 131 m^2, diameter of the drum is 1,5 m and the length of drum is 6,3 m.**

The important part of this thesis is the economical evaluation. The paramount part of this evaluation is the price of the fuel and the dryer. The price of fuel (wood chips) varies from each supplier. Special offers and deals are normally available. Based on consultations with the thesis supervisor and a survey of suppliers; **the price of wood chips with moisture content of 60% was found to be 130 CZK/GJ. The investment cost of a dryer was estimated at 2 500 000 CZK.**

This evaluation compares the two options of a boiler operation. In the first option, the boiler burning wood chips with **moisture content of 20%,** are purchased for a price **170 CZK/GJ.** In the second option wood chips are bought with a **moisture content of 60%** for a price of **130 CZK/GJ**. Once the wet wood chips are dried in the steam drum dryer they are then burnt in the boiler. The payback of the dryer investment is based on the fuel cost saving. Despite the additional operational costs of the drying process, **the payback is 6,5 years. Discount payback is 10 years.**

In terms of the economical evaluation objectivity, the "what-if" analysis was executed, to monitor the behavior of payback in relation to dryer investment, operational hours and price of fuel. The presented "what if" analysis proves significant dependence on payback to the dryer investment cost and fuel price. The payback period will be strongly affected by the change of these parameters. Based on the presented analysis, it was possible to determine the exact values of the fuel cost, number of operational hours and the dryer investment cost in order to achieve the payback over a 10 year period. **Fuel price per unit – 130 CZK/GJ, number of operational hours – 5000 hour/year and dryer investment cost – 2 400 000 CZK**.

The use of a drying machine is beneficial for the given project. This statement is based on the results of experiments, calculations, design, evaluations and analysis. The drying machine brings significant fuel cost savings, despite the additional operational costs of the drying process. The payback of investment is only 6,5 years which makes this machine a very viable proposition.

The dryer uses renewable sources and because of the way it uses steam it can be said that this machine could be environmentally sound.

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