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Straw biomass processing to solid biofuels

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Declaration

I declare that the presented bachelor´s thesis entitled “Straw biomass processing to solid biofuels” was prepared separately with use of the referred literature and laboratory research. I agree with the storage of this work in the library of CULS in Prague and making it available for further study purposes.

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Date Signature

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ABSTRAKT

Kvůli tomu, že se světové zdroje fosilních paliv ztenčují, je nutné hledat nové zdroje energie. Za vhodný zdroj energie je v současnosti považována odpadní biomasa ze zemědělské produkce, zejména sláma, která je dostupná, levná a obnovitelná. Sláma má podobné vlastnosti jako dřevo, ale díky své nízké hustotě není vhodná pro přepravu a manipulaci na větší vzdálenosti. Tento problém může být vyřešen lisováním do pelet, které mohou být použity v automatických kotlích. Spalování slámy s sebou nese také problémy s některými jejími vlasnostmi, jako jsou spékání popela nebo koroze tepelných výměníků v kotlích (kvůli uvolňování chlornatých sloučenin). Tyto problémy mohou být omezeny přidáváním zlepšujících minerálních materiálů (aditiv) jako je například vápenec nebo uhlí nebo energogenních materialú (odpadní papír, staréhadry, atp.). Parametry pelet důležité pro jejich využití jsou výhřevnost a mechnická odolnost; ty byly předmětem zkoumání této práce. Po rešeršní činnosti v oblasti literatury týkající se pevných biopaliv, experimentální část byla zaměřena na lisování pelet z pšeničné slámy ve směsi s uhlém (prach z hnědého uhelí) ve třech různých poměrech. U vyrobených pelet byla testována jejich výhřevnost a mechanická odolnost. Testy ukázaly, že hnědouhelný prach významně ovlivňuje výhřevnost, která rostla s procentickým obsahem uhlí. Mechanická odolnost byla přidáváním uhlí ovlivněna negativně. S přidáváním uhlí do pelet klesala jejich odolnost. Oba tyto jevy byly na základě prostudované literatury hypoteticky očekávány, cílem práce však bylo zjistit kompromisní obsah uhelného prachu, který by zajistil vyšší spalné teplo i přijatelnou mechanickou odolnost pelet.

Klíčová slova: sláma, biomasa, biopaliva, uhlí, pelety, aditiva, splané teplo, mechanická odolnost

ABSTRACT

While worldwide sources of fossil fuels are getting depleted it is necessary to search new energy sources. At present as a suitable source of energy is considered biomass from agricultural production, especially wheat straw, which is available, cheap and renewable. Straw has similar properties as wood but due to its low bulk density it is not well usable for transport and manipulation in greater distances. This problem can be solved by pressing pre-processed straw into pellets which can be used in automatic boilers. However, the following combustion of straw causes also problems due to some its properties which cause ash melting or corrosion of heat exchangers in boilers (for reason of higher contents of clorin sudstances). These problems can be reduced by adding some improving materials (as additives) such as limestone or coal. Important parameters of pellets at their utilization are calorific value and mechnical durability which were investigated in this Thesis. After an extensive literature analysis this work focused on production of mixed pellets from wheat straw mixed with brown coal dust and their properties. In its experimental part the mixed pellets were pressed in three different ratios of wheat straw and brown coal dust. The produced pellets were tested on mechanical durability and calorific value. The tests have showed that brown coal dust has significant positive influence on calorific value which increases with higher percentage of coal conctents. The mechanical durability of pellets was influenced by adding coal negatively. With adding coal to the pellets their durability considerably decreased. Both of two phenomena were hypothetically expected thanks to information from the studied literature. It is why the Thesis goal was to find a compromising content of brown coal dust contents which would insure increase of the pellet caůlorific value at acceptable mechanical durability.

Key words: straw, biomass, biofuels, coal, pellets, additives, processing, calorific value, mechanical durability

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List of Abbreviations

- AB Agricultural Biomass
- AD Anaerobic Digestion
- CR Czech Republic
- EU European Union
- HHV Higher Heating Value
- Kč Korun českých
- LHV Lower Heating Value
- MPO Ministerstvo Průmyslu a Obchodu
- MZe Ministerstvo Zemědělství
- RB Residual Biomass
- SD Standard Deviation
- U.S. United States
- VÚZT Výzkumný Ústav Zemědělské Techniky

I. INTRODUCTION

While worldwide energy consumption still increases the reserves of fossil fuels are considerably getting depleted. With the impending shortage of energy resources world faces problems of lack of energy. Increasing consumption of fossil fuels also brings up questions about their impact on environment which is currently one of the most arguable themes.

As one of the sources suitable for their replacing could be biomass. Biomass is renewable, relatively cheap and does not affect the environment in such an extent as fossil fuels thanks to CO_2 production – consumption balance. It is related to the biomass ability to absorb CO_2 from atmosphere during growth which is during combustion again released to the atmosphere. In contrast to fossil fuels the combustion of biomass is in zero ratio of releasing CO_2 therefore utilisation of biomass affects environment less than fossil fuels such as coal or oil (Havrland *et* al., 2011). As biofuels on the base of mainly woody raw material from forests (wood extracition and processing) are utilized but currently it is also evident lack of these materials (Larsson *et* al., 2011).

Recently many authors have focused on utilization of residues from agriculture production such as straw which is available in large amounts. During last decades with intensification and decrease of cattle breeding large amounts of these materials which have almost similar properties as woody materials get aside and are unutilized. Only in Czech Republic about 3.7 million tons of cereal and rape straw is available (supposed if only 50% of their total production were used) (Abrham *et* al., 2012).

The straw is also relatively stable source of renewable energy in comparison to solar or wind energy which are more dependent on weather conditions and period of day. However some defficiencies especially linked to its properties which make problems during combustion (ash meting) and transport (low bulk density) call for its processing into biofuel. In comparison with wood fuel the straw contains higher amount of chlorine which causes corrosion of metallic combustion equipment. Also its ash melting point temperatures are lower than the one of wood which requires special treatment and optimization of this fuel composition and combustion process. Due to its low bulk density the straw is currently used as local source of energy because of high transport costs in comparison to other fuels such as coal or wood. The straw compaction by way of pressing is one of the possibilities how to solve this problem.

The briquettes and pellets made of wood are normally used for heating in family houses or in boilers of larger (public and company) buildings. The straw briquetting is also advantageous from the viewpoint of bulk density, however the briquettes require periodical hand stoking into the boilers or stoves in contrast to pellets which are (can be) stoked automatically. Nowadays the people do not have a time for periodical stoking fuel to the boilers and this problem can be solved by fuel pellets.

Recently there have been only few stove or boiler types for combustion of these alternative fuels such as straw pellets available on the market. Because of some negative properties of straw projected into the pellet technical properties it is necessary to find possibilities of their improving. One of these options is adding some improving materials (additives) to the straw which could increase temperatures of ash fusibility (melting) or prevent corrosion effect.

Thus, the straw is a suitable material for energy production by ecologic way without influence on CO_2 concentration in the atmosphere or impact on prizes of food production. Its constant production makes straw one of the reliable energy sources which can, in the future, replace fossil fuels but it is necessary to test and develop optimum ways (compositions, production technologies, combustion facilities, etc.) of its production and utilization.

However, another fact was as leading motto to this Thesis focus. The brown coal dust which origins from brown coal processing and is considered as an unuseful difficult pollutant. Its burning is usually uncomplete and emissions highly surpass values given by relevant standards. It can be used as additive to biofuels (not only pellets) whereby the resulting emissions produced by their combustion do not violate the standards. By such a way the brown coal turns into component of a valuable biofuel.

The present thesis addresses issues as discussed above. I.e. it attempts to combine components of renewable and fossil raw materials which would enable to produce heat at lower emission level whereby using brown coal considered as highly polluting fossil fuel. In this work the main focus is paid to pellets produced from mixtures of wheat straw and brown coal dust in different ratios. The experimental part of this thesis focuses on testing their calorific value and mechanical durability which was compared with results of other authors. Also some properties of raw materials were determined as of high importance for final products (pellets). The acquired results have been compared with other authors and with different types of pellets.

II. LITERATURE REVIEW

2.1. Biomass

Biomass is known as a source of energy since the beginning of people existence. Using of biomass as a fuel in the past was indispenseble for people activities such as heating of households, iron smelting or producing of gunpowder (Valečko, 2004). During the time of industrial revolution in the last two centuries there has been intesive use of fossil fuels which leads to increased concentration of CO_2 in the atmosphere (Ochodek *et* al., 2006). Use of fossil fuels for energy production is now facing serious problems related to resource depletion and environmental degradation. Biomass fuels are, on the other hand, renewable in relatively short time period and carbon neutral (Nguyen *et* al., 2013). According to Naik *et* al., (2010) biofuels made from materials such as plants or organic waste reduce CO_2 production and dependence on oil. Burning biomass release the same amount of CO_2 as tied up during its growth. Therefore it does not increase CO_2 in the atmosphere and is suitable for production of solid (gaseous, liquid) biofuels (Naik *et* al., 2010).

2.1.1. Definition of biomass

Biomass is a mass of organic origin whether plant or animal origin and in contrast to fossil energy is renewable (Jurek, 2012). The term of biomass also includes materials of animal origin but these materials are not included as fuels except rendered fat which can be process to biodiesel. From the viewpoint of energy utilization is more important phytomass which is summary term for organic material arising on the basis of photosynthesis by collecting and transformation of solar energy in plants such as trees, herbs, grasses but also seaweed or algae (Andert *et* al., 2006). According to Ochodek *et* al., (2006) biomass is defined as substance of biological origin, which includes vegetal biomass planted on soil and in the water, animal biomass, production of organic origin and organic wastes. Biomass is also divided into phytomass which is only substance of plant origin and biomass which includes also animal origin substances (Ochodek *et* al., 2006). Fuels produced from biomass are renewable source of energy and are locally available in contrast to fossil fuels (Holý, 2010). Another advantage is that during the burning is released the same ammount of CO_2 as it is used during growth which does not affect growth of CO_2 in the atmosphere (Ochodek *et* al., 2007).

2.1.2. Distribution of biomass

Biomass is now used especially for heating of buildings, or biogas production, often with subsequent production of electricity. Utillization of waste materials is the cheapest source of biomass, but due to increasing number of biomass power plants are already discovered signals about a lack of forest and wood waste (Petříková, 2005). In the most cases in Czech republic (CR) is used only waste biomass from forestry production, especially wood for heating. Because people begin again to heat with wood and due to increasing prices of fossil fuels, ammount of woody biomass is rapidly decreased and it is necessary to find other sources (Červinka, 2009). Intentionally grown biomass for energy purposes is best to grow on unused agricultural soils. It is advantageous for preserving soil fertility and there are possibilities of receiving grants (Hajdová, 2011). Lewandowski *et* al. (2006) claims that previous studies in CR estimated energy potential from energy crops, agricultural and forestry residues to be about 270 - 340 PJ yearly assuming that 0.4 - 0.8 million ha (10-20 % agricultural land in CR) are available for energy crop production because the land use for food and forage production has decreased over the last decade. By origin of biomass we can classify intentionally grown biomass and waste biomass which includes also municipal organic wastes (Štěrba, 2012).

Biomass classification by Štěrba (2012):

1. Waste biomass:
    - Agricultural waste (cereal, maize, rape straw, hay, wastes from orchards and vineyards….)
    - Forest waste (stump, cones, roots, bark, branches...)
    - Organic waste from industrial production (sawdust, shaving, bark, waste from slaughterhouses, sugar mills, dairies, distilleries…)
    - Waste from animal production (manure, leftovers)
    - Municipal organic waste (sludge)
2. Intentionally grown biomass for energy purposes:
    - Trees (willows, poplars, alders…)
    - Cereals (whole plants)
    - Grasslands
    - Other plants (hemp, sorghum, sorrel)
    - Oleaginous plants (oilseed rape, sunflower…)
    - Sugar- starch plants (potatoes, sugar beets, sugar cane, maize…)

According to Lewandowski *et* al. (2006) we can classify biomass into three sources:

- Biomass from agricultural residues
- Biomass from forestry residues
- Biomass from energy crops

According to MZe (2009) we can define three main groups of biomass:

1. Agricultural biomass (AB):
    - intentionally grown biomass
    - biomass of cereals, oilseeds, fiber crops
    - permanent grasslands
    - fast- grown trees on agricultural land
    - crop residues from agricultural primary production and landscape maintance

AB (phytomass) is the most comprehensive part of biomass potential in CR. The effect of alternative crops is in energy self- sufficiency of rural areas, increasing attractiveness of municipalities and regional consumption of produced financial resources. But it is necessary to solve relatively challenging logistic and processing technologies. For energy conversion is posibble to use part of agricultural by-products (straw) or unused hay from maintance of meadows. Posibble is also production of crops for non-food purposes, fast-grown trees or intetonally energy crops and grasses.

2. Forest biomass (dendromass):
    - firewood
    - residues from forestry maintance

As a fuel can be used especially residual dendromass from forestry maintance and timber industry. Current calculations of forest biomass potential are based only on values from toll mining and provided that 20% of dendromass stay on the mining area, but there are other sources, such as thinnings , which are not calculated.

3. Residual biomass (RB) is created by residues and by-products:
    - paper industry
    - food industry
    - timber processing industry
    - animal industry

- other industry
- biodegradable waste
- distillery industry

RB includes wide range of materials arising secondarily during processing of primary biomass sources. The main volume of residual biomass comes from paper industry, timber industry, food industry (meat processing) and from sorting of municipal waste. We can also separately include sewage sludge and sludge from specific productions classified as biomass.

2.1.3. Energy utilization of biomass

From the energy point of view is even today the most common final use of biomass combustion. According to the form, biomass is combusted directly, or combusted are gaseous or liquid components of its processing (Jakubes *et* al., 2006). Method of uttilization is largely destined by physical and chemical properties. One of the important properties is content of dry matter. If the dry matter content is less than 40% we talk about the wet processes, while if the content of dry matter is higher than 40%, it is a dry process (Červinka, 2009). Not all biomass is suitable for thermal utilization and method of processing varies by purpose for small or big equipment (sources). Higher rate of processing is unnecesary for small sources (household boilers), where is usually use more quality types of fuels (pellets, briquettes). In bigger sources is possible to use minimum processed biomass such as crushed forest residues, straw bales and more (MZe, 2012). According to current prognosis has the biggest rolle biomass for direct combustion. It is used for electric production, heat production, even in substitution of coal in households. Less importance have liquid biofuels or biogas. According to Hajdová (2011) the basic technologies of processing and preparation of biomass for energy utilization are distinguished:

a) Thermo-chemical conversion *(dry processes):*
    - combustion
    - pyrolysis
    - gasification
b) Biochemical conversion (*wet processes):*
    - alcohol fermentation
    - anaerobic digestion and fermentation of organic waste
    - composting

c) Physical and chemical conversion

- mechanically (splitting, crushing, compacting, briquetting, pelleting, grinding)
- chemically (esterification of unrefined bio-oils)

a) Thermo-chemical conversion

- **Combustion**

Combustion is chemical reaction between fuel and oxygen which is available from air. During combustion arise carbon dioxide and water with the release of heat. Biomass combusted in domestic stoves or boilers, wich are well vented, can be used as substitute of conventional fossil fuels (Naik *et* al., 2010). Producted thermal energy can be used for heating, technological processes, water heating or electric energy production. Advantage is that for combustion technology are not required special treatments of biofuels. Possible is also burning of biofuels with higher mosture content. Important condition of perfekt combustion is high temperature, effective mixing with air and enough space in combustion area, because released gases should be burned in chamber, not in chimney. That is why is important monitoring of emission of carbon monoxide and solid substances (Červinka, 2009). Burning of biomass is currently resolved in two conceptions: burning on grate or combustion in fluidized bed (Motlík *et* al., 2002).

Combustion process is consisted of four phases (Budiš, 2011):

1) **Drying-** material is heated and loses monture.
2) **Pyrolysis-** after achieving incendiary temperature, in the presence of air begin decomposition of organic material into flamable gases, distilery products and charred rest.
3) **Combustion of gaseous components-** gaseosus components are gradually burned.
4) **Combustion of solid components-** in sufficient presence of oxygen are burned solid components, arise carbon monoxide and is next oxidated into carbon dioxide.

- **Pyrolysis**

According to Naik *et* al., (2010) pyrolysis is thermal degradation of biomass by heat in the absence of oxygen, which results in the production of charcoal (solid), bio-oil (liquid), and fuel gaseous products. Pyrolysis is heating of the material above the limit of thermal stability of the present organic compounds which leads to cleavage on permanent low-molecular products and solid residues (Staf, 2005). Staf (2005) also claims that pyrolysis can be divided by achieved temperature during process:

- Low-temperature (< 500 °C)
- Medium- temperature (500 – 800 °C)
- High-temperature (> 800 °C)

The rest of energy from combusted gasses which is unused for heating is used in boilers for generating of steam or warm utility water. Pyrolysis gas can be used also as a chemical material or as a fuel for engines or gas turbines of cogeneration units (Červinka, 2009).

- **Gasification**

Biomass can be in solid or liquid state. It is superior way of transformation which happens in higher temperatures and with limited inflow of oxygen (Červinka, 2009). Gasification is complex process of many reactions. In general view there are four basic processes: drying, pyrolysis, reduction and oxidatition. These processes can take place gradually (fixed bed generators) or simultaneously (fluidized bed generators) (Pohořelý *et* al., 2010). Product is gas which contains heating components (H_2, CO, CH_4), companion components (CO_2, H_2O, N_2) and polluting components (tar, dust, sulfur, chlorine, alkali and other). Producted gas is always acompanied with polluting components which must be separated (Pohořelý *et* al., 2010). According to Motlík *et* al. (2002) calorific value of produced gas is between 4 - 6 $MJ*m^{-3}$ and can be used in boiler burners and after additional separation of pollutants in chambers of combution turbines and in modified engines.

b) Biochemical conversion

- **Alcohol fermentation**

Alcohol fermentation takes place in wet conditions without air and final product of fermentation is bioethanol (Budiš, 2011). The most important crops in ethanol production in CR are winter wheat, soybean, sugar beet, maize or potatoes. Difference between food and pharmaceutical ethanol and bioethanol is that during process of distilation, refining and dehydration are not separated some group of substances (Strašil, 2009). Bioethanol is possible to produce from almost all materials, which contain starch or sucrose. Leading position in production holds maize in U.S. and sugar cane in Brazil. In EU is for production of bioethanol used especially cereals and sugar beet (Číž, 2010). According to Hromádko *et* al., (2011) the ethanol production can be divided into three groups by type of biomass:

- biomass contains monosaccharides (sugar beet and sugarcane)
- biomass contains starch (cereals)

- biomass contains lignocellulose (straw, fast-growing trees, wood chips, biological origin waste, paper, etc.)

Bioethanol production from sugar beet or cane is simplest. These materials contain sucrose, which is transformed into monosaccharides which can be simply separated and fermented. In condition of CR prevails bioethanol production from cereals. Production from lignocellulose biomass is relatively complicated and currently is object of intense research activity. Into materials suitable for lignocellulose biomass fermentation includes fast-growing trees (willows), agricultural residues (straw, pressed sugarcane) or wood wastes (bark, sawdust) (Hromádko *et* al., 2011).

- **Anaerobic digestion (AD)**

AD is perspective way of ecological biomass utillization. In literature we can find terms like anaerobic fermentation or methane fermentation, but all these terms have the same meaning.Simplified we can say that AD is biological decomposition of organic matter in an anaerobic environment. Final product is biologically stabilized substrate (digestate) with high fertilization potential a biogas with methane content of 55 - 70% and calorific value about 18 - 26 MJ*m^{-3} (Mužík *et* al., 2009). AD is multistage process in which is organic matter decomposed by microorganisms on final products. Biogas production includes four phases (hydrolysis, acidogenesis, acetogenesis, methanogenesis). For each phase are optimal different conditions because of different bacterias which are applied during process (Fuksa *et* al., 2009). Temperature influences AD like other biochemical processes- with increasing temperature increases speed of all processes. For stability of AD is important to keep constant temperature.

Normally there are three typical temperature ranges which are suitable for bacterias (Mužík *et* al., 2009).

- psychrophilic temperatures (< 20 °C)
- meyophilic temperatures (25-40 °C)
- thermophilic temperatures (> 45 °C)

$$\mathbf{C_6H_{12}O_6 \Rightarrow CH_4 + 3CO_2 + digestate + heat} \qquad (1)$$

According to Mužík *et* al., (2009) biogas is used especially for direct combustion, cogeneration of electric energy or as a fuel for combustion engines or turbines.

- **Composting**

Composting is way of utillization biodegradable wastes for production of organic fertilizer-compost. Organic matter is transformed on humic components predominantly by aerobic microorganisms. For optimal conditions is necessary to use correct ratio between carbon and nitrogen (C:N) by suitable materials in fresh compost. C:N ratio in fresh compost should be between 30 - 35:1. Wider C:N ratio makes longer period of compost maturation (Váňa, 2002).

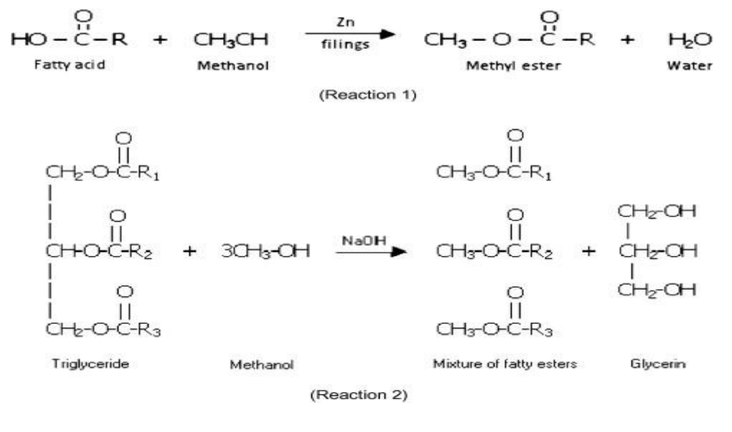
By composting is returned energy back to the soil and it can be used again by plants. Compost also improves soil workability, increases sorption capacity, aerates soil or decreases acidity. Content of nutrients dependent on input materials and in average compost from biological waste can contains 5 - 16 kg of nitrogen in one ton (Šrefl, 2012).

c) Physical and chemical conversion

- Esterification

This technology in which the esterification of natural oils and fats with methanol in the presence of alkaline catalyst (NaOH, KOH) is produced methylester (Budiš, 2011). Methylester has similar properties and calorific value as diesel (45 - 49 $MJ*kg^{-1}$), but its degradability in nature is faster then in common diesel and also emissions are better. Under the term of "biodiesel" is used for mixture of methylester and common diesel (Stupavský, 2008)(Červinka, 2011). In conditions of CR is used oil from oilseed rape and resultant methylester is called MEŘO. Disadvantage is that in current conditions is production still more expensive than common diesel (Budiš, 2011).

Figure 1.: Biodiesel production: free fatty acids esterification catalyzed by metallic Zn filings (Reaction 1); triglycerides transesterification catalyzed by NaOH (Reaction 2)



Source: Corro et al., (2012)

- **Mechanical treatment**

Mechanical treatment lies in transformation of biomass into required shape, form and proportions. The resulting biofuels are more suitable for storage. Take up less volume and have better properties for other energy utillization. These solid biofuels are mainly used for direct combustion (Budiš, 2011). Higher evaluation can be reached by producing fuel briquettes or pellets from many different materials such as wood or straw. For purposes of mechanical treatment are used equipments such as mowers, shredders, grinders, chippers, presses, saws etc. Some of these equipments will be discussed in other chapters.

2.2. Solid biofuels

Solid biofuels created from plant biomass are alternative to fossil fuels used in stationary sources of heat and in the future will increase their use. It is assumed that share of biofuels on total energy consumption will continue to rise, especially in the case of intentionally grown biomass for energy purposes (Hutla *et* al., 2012). Fuels made from biomass such as agricultural products, including plant and animal materials, forestry products, wastes and residuals biologically decomposable and industrial or household wastes biologically degradable are called as biofuels. Energy biomass is divided into three groups according to its energy utilization. Solid biomass is used for direct combustion and heating of buildings, gaseous biomass for biogas production and liquid biomass for produciton of biodiesel or bioethanol. According to Petříková (2008) solid biomass is the most significant from these forms because of its use in the area of production without need of trasportation for large distances (especially rural areas) and also for its lower energy demads in procesing in contrast to biodiesel or bioethanol. Using of wood, forest or agricultural wastes such as straw or sawdust for solid biofuels is advantageous because of their lower cost than in the case of intentionally grown energy biomass (Petříková, 2008).

Table 1.: Production of electricity and heat from renewable sources and waste in the CR

Indicator	**2005**	**2008**	**2009**	**2010**	**2011**
			Electricity (GWh)		
Hydroelectric power plants	3 027	2 376	2 983	3 381	2 835
Wind power plants	21	245	288	335	397
Solar power plants	2	13	89	616	2 118
Solid biomass	560	1 171	1 396	1 492	1 683
Industrial wastes	0	2	2	2	5
Municipal wastes	18	21	18	60	150
Biogas	161	267	441	635	933
			Heat (TJ)		
Solid biomass	40 892	43 400	43 007	46 736	47 750
Industrial wastes	5 196	5 983	6 283	5 929	5 920
Municipal wastes	3 420	3 146	2 743	2 973	3 460
Biogas	1 010	1 065	1 211	1 610	2 379
Heat pump	510	1 160	1 445	1 776	2 200
Solar thermal collector	103	204	266	366	455

Source: Ministry of Industry and Trade of the CR, (2012) According to table solid biomass is the third biggest renewable source of electricity production and the biggest renewable source of heat production in CR. In a large heating plants or power plants are most often used wood chips or straw in bales, but for heating smaller buildings such as households is necessary to adjust biomass to a suitable form, which can be easy manipulated during adding fuel to the stoves or can be added automatically by dispensers (Petříková, 2007).

Solid biofuels are known in several forms which are different in many aspects such as water content, calorific value, ash content, shapes etc. Level of processing and treatment varies as well as cost and useful value (Andert *et* al., 2006). Alakangas *et* al. (2006) divides solid biofuels into sub-categories by origin and source of biomass according to CEN/TS 14961:

- Woody biomass
- Herbaceous biomass
- Fruit biomass
- Blends and mixtures

Group of „Blends and mixtures“ is divided into intentionally mixed blends in known ratios and unintentionally mixed mixtures (Alakangas *et* al., 2006). Fuels from woody biomass are distinguished as: wood logs, bark, chips, sawdust, wood shavings, pellets and briquettes. From herbaceous biomass are the most used residues from cereal production.

Straw can be processed into the form of cylindrical or angular bales, crushed into the chopped or pressed into briquettes and pellets (Andert *et* al., 2006). Jevič *et* al. (2008) also mentions fruit peels and kernels as a traded form of solid biofuel and also residues from pressing. According to MPO (2011) in CR for electricity and heat production outside the households are mostly used wood chips and wood waste. Especially in heat production in 2011 was consumed about 1 million tons of wood chips and waste which produced 1.8 TJ of heat for sale. Tables 2 - 4 show that annual consumption of biofuels in households grows continuously and during the years 2003 - 2011 increased by almost 1 million tons (MPO, 2011).

Table 2.: Electricity generation from biomass as their types in 2011

	Respondents	Electricity generation (MWh)	Self-consumption with losts (MWh)	Supply to the network (MWh)	Fuel consumption (t)
Firewood	0	0,00	0,00	0,00	0,00
Wood chips, waste	29	820 001,02	141 454,64	678 546,38	845 217,55
Cellulose digests	2	526 202,84	498 129,64	28 073,20	266 494,20
Plant materials	7	111 020,57	11 985,25	99 035,32	94 979,77
Briquettes, pellets	10	218 019,51	31 104,59	186 914,92	143 491,44
Other biomass	0	0,00	0,00	0,00	0,00
Liquid biofuels	9	9 327,24	9 221,49	105,75	1 584,03
Total	**45**	**1 684 571,17**	**691 895,61**	**992 675,57**	**1 351 766,99**

Source: MPO, (2012)

Table 3.: Heat generation from bimass as their types in 2011

	Respondents	Electricity generation (GJ)	Self-consumption with losts (GJ)	Supply to the network (GJ)	Fuel 1consumption (t)
Firewood	517	360 065,22	360 065,22	0	34 652,98
Wood chips, waste	684	8 415 716,72	6 613 993,57	1 801 722,95	1 005 721,78
Cellulose digests	2	6 609 280,62	6 437 996,52	171 284,10	833 133,40
Plant materials	59	429 334,32	69 815,72	359 518,60	40 265,96
Briquettes, pellets	151	316 126,41	132 594,50	183 531,91	23 087,26
Other biomass	0	0	0	0	0
Liquid biofuels	4	2 102,10	1 361,90	740,20	99,87
Total	**1178**	**16 132 625,39**	**13 615 827,43**	**2 516 797,76**	**1 936 961,25**

Source: MPO, (2012)

Table 4.: Estimation of biomass consumption in households

Year	Consumption (t)	Energy in use fuel (GJ)	Heat (GJ)
2003	2 653 477	34 495 195	21 820 358
2004	2 827 363	36 755 715	23 250 277
2005	2 852 206	37 078 678	23 454 572
2006	3 087 549	40 138 138	25 389 871
2007	3 585 103	46 606 334	29 481 407
2008	3 397 340	44 165 424	27 937 379
2009	3 345 303	43 488 936	27 509 459
2010	3 729 701	48 486 113	30 670 484
2011	3 563 541	46 326 036	29 304 101

Source: MPO, (2012)

2.2.1. Forms of solid biofuels

- **Wood logs**

Firewood in the form of logs prevail in heating of households and farms in rural areas (Andert *et* al., 2006). Size of logs is limited by size of stoking hole and combustion chamber. Into larger boilers is possible to stoke logs up to length of 1 meter, but in households is common use boilers for logs in lengths between 0.25 - 0.5 m (Stupavský, 2010). Processed wood for combustion is recommended to dry out to less than 30% content of water. It also increase calorific value from about 8 $MJ*kg^{-1}$ to 12 - 14 $MJ*kg^{-1}$ (Andert *et* al., 2006). Calorific value varies by type of wood, water content, hardness or by content of lignin and resin. But calorific value is not always the main requirement. Coniferous woods have got great calorific values but are burned so fast and chimney is ussualy clogged by resin. Therefore is prefered hard wood such as oak, hornbeam, beech, ash and some fruit trees which is burned with adequate intensity (Grozman, 2012).

- **Wood chips**

It is wood mass choped and crushed on particles of length 3 - 250 mm. Chips are obtained from forest logging wastes and industrial processing of wood or fast-grown trees. Wood chips are really cheap biofuel especially for heating of larger buildings. According to quality, chips from forest logging wastes can be divided into three groups. Green chips include ussually leaves or needles and has highest water content which can be about 55% immediatelly after logging.

Brown chips are obtained from residual parts of strains and includes bark. White chips are obtained from sawmills, doesn´t incude bark and is used for hardboard desks. Calorific value varies according to water content from 8 - 12 MJ*kg^{-1} (Stupavský *et* al., 2010). Andert *et* al. (2006) divides chips into three groups by water content and recommends final drying on the grates. Chips from wastes of woodwork have water content about 15% and calorific value is highest from chips about 15 - 16 MJ*kg^{-1} (Andert *et* al., 2006).

- **Briquettes**

As a source for briquettes production can be any plant material. Mostly is used woody biomass such as sawdust and shavings but recently are produced also from straw and from mixtures of herbaceous and woody materials (Piszczalka, 2012). Briquettes are produced by pressing into different shapes according to the type of pressing machine. On the market are available in kapes of cylinders, prisms or hexadrons with diameter 40 - 100 mm and length up to 300 mm independently on the material (Stupavský *et* al., 2010b). Briquettes can be used in smaller furnaces, stoves, boilers or fireplaces, all with manual stoking. Andert *et* al. (2006) distinguishes two main groups:

  - Wood briquettes

Dry wood brash, sawdust and shavings with water content of 6 - 12% are mechanically pressed by work pressure from 20 - 100 MPa into final products with density 600 - 1200 kg*m^{-3}. Calorific value is ussualy about 16.5 - 18.5 MJ* kg^{-1} and ash content in dry matter is 0.5 - 1.5%. Content of pollutants is determined by norm.

  - Briquettes from stalk plants

Pressed cereal straw, oilseed straw, grasses, energy herbs with water content between 8-14%. Briquettes have similar density and calorific value as wood briquettes except briquettes from oilseed straw which can reach calorific value about 19 MJ*kg^{-1}. Ash content is higher about 5 - 6%. According to norm is possible to use ecoogical binder and additives (Andert *et* al., 2006).

- **Pellets**

Pellets are form of ecollogically noble biofuel produced from biomass, which is suitable for automatic combustion in special boilers (Verner, 2007). Crushed biomass is mechanically pressed into cylindrical shape. Diameter of cylinders is between 6 - 20 mm and lenght between

10 - 50 mm. Ratio between diameter and lenght should not be higher than 1:3 (Andert *et* al., 2006). According to Verner (2007) pellets can be divided into two main groups:

- wood pellets
- alternative pellets

Wood pellets are further divided into white and dark pellets. White pellets are produced from clean wood mass (mainly sawdust) without bark. Dark pellets include sawdust with crushed bark. Alternative pellets are produced especially from plants and their parts, and are further divided into agropellets and others. Agropellets are pressed from agricultural comodits such as energy plants, cereal and rape straw, wastes after processing of cereals and oilseeds or from hay. Others pellets are pressed from otherwise hardly usable materials such as crushed old paper or coal dust. These materials can be added to agricultural comodits and pressed according to standards (Verner, 2007). Production of pellets is relatively challenging due to energy and technical requirements. It is necessary to ensure knowledge of personal serving the pelletizing machine and ensure the quality and stability of input material. Important properties of input material are especially moisture and particle size. Input material should have stabilized water content about 10 - 12%. Material with higher moisture is better pressed and pellets are in the beginning more resistant to mechanical damage, but in a short-term period after pelletizing begin crumble. Particle size of material should be the smallest as it is possible due to strength of pellets.

The finer particles have larger surface area for connection during pressing. Material is usually crushed on the sieves with openings 4 - 6 mm. Another important step in pelletizing is wetting input material just before is pressed. It releases adhesive substances from surface of material and hold particles together (Kott, 2010). Kott (2010) also claims that is more advantageous to use water vapour which incerase productivity of press, than use cold water. According to Verner (2007) there are differences between wood pellets and alternative which are important especially due to final use in boilers and stoves. Wood pellets are known for low ash content about 0.5 - 2.5% and calorific value between 17.5 - 19.5 $MJ*kg^{-1}$. Alternative pellets have higher ash content between 1-9% according to material and calorific value between 15 - 18 $MJ*kg^{-1}$. Due to higher ash content and lower melting point of ash alternative pellets can not be burned in wood pellet boilers which are the main disadvantage of this material. On the other hand heating season of family house with alternative pellets costs about 10000- 17000 Kč and in contrast to wood pellets (20000-30000 Kč) is much more cheaper and almost comparatively comfortable (Verner, 2007).

2.2.2. Properties of solid biofuels

According to Jevič *et* al., (2008) the quality and properties of solid biofuels are examined and assessed in two groups of parameters. Chemical properties include content of chemical elements but also water, ash and spores of fungi content. Further are in this group included calorific value and ash fusibility which are important indicators for combustion equipments. Physical properties include dimensions of biofuels, particle size, density, mechanical resistance etc. (Jevič *et* al., 2008). For a long-term sustaining of quality of biofuels is necessary to know their quality and composition which affects also combustion and impact on environment (Kotlánová, 2009).

a) Chemical properties

Except main components (C, H, O) are in biomass contained other elements which affects combustion and emission properties such as N, Cl, S, K and also heavy metals (Jevič et al., 2008). Biofuels in contrast to fossil fuels contain high ratio of oxygen which decreases calorific value but also allows better burning of flue gassses which reduce releasing of emissions to the air. According to table chemical components varies by type of biomass. Wood biomass is created mainly by C, H, O with low ash content. Stalk plants contains higher ratio of elements such as N, Cl, S and also higher ash content (Janíček, 2011).

Table 5.: Chemical components of straw and wood pellets

Component	Unit	Wheat straw pellets	Spruce wood pellets
Ash	% m/m	3,33	0,58
C	% m/m	43,04	46,24
H	% m/m	6,51	5,6
N	% m/m	0,72	0,08
S	% m/m	0,05	0,01
O	% m/m	36,89	39,91
Cl	% m/m	0,09	0,04

Source: Jevič, (2008)

- **Nitrogen**

During combustion is N contained in biofuel almost completely transformed into gaseous N_2 and NO_x, NO, NO_2 and only an insignificant amount is contained in the ash. Higher value of nitrogen ussually shows bark and logging residues, short rotation trees (willow, poplar) and grain straw. NO_x emissions caused one of the main impacts of solid biofuels combustion (Obernberger *et* al., 2006).

- **Chlorine**

According to Obernberger et al. (2006) Cl content in wood biomass is ussually very low in contrast to biofuels from herbaceous material. During combustion is Cl transformed to gasseous HCl, Cl_2 and alkali chlorides. The corrosive effect of Cl on the surface of furnace and boiler is noticable especially during combustion of herbaceous material. According to Jevič *et* al., (2008) higher content of Cl can also leads to decreasing temperarure of ash fusibility.

- **Sulphur**

According to Obernberger *et* al., (2006) is S transformed during combustion mainly into gaseous SO_2, SO_3 and alkali sulphates. SO_x forms sulphates which condenses on the surface or reacts with fly ash deposited on the heat exchanger (sulphation). S has indirect corrosive effect because at higher concentration of SO_2 in flue gas occurs to sulphation on the surfaces which release corrosive Cl (Jevič *et* al., 2008).

Table 6.: Content of N, Cl, S in selected biomass

Element	**Spruce wood (mg/kg)**	**Spruce bark (mg/kg)**	**Wheat straw (mg/kg)**	**Triticale (mg/kg)**
N	900-1700	1000-1500	3000-5000	6000-14000
Cl	70-1000	100-2000	500-1100	1000-1200
S	50-60	100-370	1000-7000	1000-3000

Source: Janíček, (2011)

- **Carbon, hydrogen, oxygen**

C, H and O are the main components of solid biofuels. C and H are oxidised during combustion and have possitive effect on gross calorific value in contrast to O which has negative effect. Higher content of C is contained in wood fuels than in herbaceous materials which explains higher GCV. The main product of combustion is CO_2 but during planting is consumed the same ammount of CO_2 as is released during combustion therefore the combustion of biomass has not effect on greenhouse gas in the atmosphere. Problems with pollutants released during incorrect combustion such as tar, soot, carbon monoxide can be resolved by appropriate combustion process which can be affected by good mixing of fuel and air, sufficient retention time at high temperatures etc. (Obernberger *et* al., 2006).

- **Content and properties of ash**

According to Janíček (2011) biomass ash consists of miwture of oxides and anorganic elments such as K_2O, Na_2O, CaO, MgO, Fe_2O_3, Al_2O_3, SiO_2, P_2O_5. In contrast to fossil fuels biofuels contain relatively small ammount of ash. Stalk plants contain higher values of ash between 6-12% of dry mass. For example wood chips contain about 0.8 - 2.5% of ash according to degree of pollution. Ash content of solid biofuel is determined by burning to a constant weight according to the ČSN P CEN/TS 14775 (Janíček, 2011). According to ČSN ISO 540 are determined 4 temepratures of ash fusibility:

Table 7.: Temperatures of ash fusibility (°C)

Fuel	Deformation	Softening	Melting	Flowing
Wheat straw	**612**	**767**	**1044**	**1257**
Rape straw	**633**	**665**	**1452**	**1460**
Wheat grain	**612**	**727**	**772**	**792**
Spruce wood	**1041**	**1180**	**1265**	**1310**
Brown coal	**1260**	**1280**	**1360**	**1500**

Source: Jevič, (2008)

- **Water content**

Water content remarkably influences calorific values and also transportation costs (Janíček, 2011). According to Kotlánová, (2010) water content influences also quality of briquettes and pellets for which is one of limiting factors. Non-water biomass does not occur in nature therefore must evaporates during combustion. Water content above 16% leads to biological processes of degradation and transformation which are associated with heat losses (Jevič *et* al., 2008). Jevič *et* al., (2008) also reported that during storage of amount of wet fuel there is a risk of spontaneous combustion which can be caused by respiration of still living parenchyma cells. This danger exists in the case of wet straw bales storage or storage of sawdust or bark.

Water content in biomass can be affected by conditions of harvest, storage and by drying. In pellets and briquettes is water content determined according to ČSN P CEN/TS 14774-1 (2,3). In wood pellets should be water content up to 10% and in briquettes up to 12% of weight. The water content in herbaceous pellets and briquettes should be up to 15% of weight (Kotlánová, 2010).

- **Calorific values**
  - *Higher heating value*

According to Jevič et al. (2008) HHV is ammount of heat released during combustion including condensation heat from water vapor. Because condensation heat contributes to energy yield HHV has got ussualy higher values than lower heating value. Mainly for wet fuels is heat efficiency of combustion decreased when with outcoming flue gas leaves also vater vapor without uttilization of condensation heat (Jevič *et* al., 2008).

  - *Lower heating value*

According to Janíček, (2008) LHV is higher heating value reduced by vapor heat of water contained in flue gases. Assessement of HHV is determined according to the ČSN P CEN/TS 14918 a DIN 51 900-3. HHV is determined in calorimeter where is the sample combusted by compressed oxygen and from the increase of temperature can be calculated HHV from which is possible to determine LHV (Kotlánová, 2010).

b) Physical properties

- **Density**

Density is an important indicator of solid biofuel quality from the viewpoint of manipulation, strength, volume and shape stability especially in the case of pressed products (Janíček, 2011). Bulk density together with calorific value is used to determine density of energy. Assessement is determined according to the ČSN P CEN/TS 15103 and results are presented in $kg*dm^{-3}$ or $kg*m^{-3}$ (Kotlánová, 2010). Density of different biofuels varies significantly. For comparsion Souček (2006) presents average density of square wheat straw bales which is 88,2 $kg*m^{-3}$ and in contrast to briquettes or pellets is low. According to Andert *et* al., (2006) can be density of briquettes from stalk plants between 600 - 1200 $kg*m^{-3}$and for pellets about 1000 - 1200 $kg*m^{-3}$.

- **Mechanical resistance**

According to Janíček, (2011) mechanical resistance can be defined as ability of pressed fuels stay intact and resist abrasion especially during manipulation and transportation. This testing is characteristic only for pellets and briquettes. This parameter is important especially for pellets which are stoked automatically and in the case of lower resistance can be this process disturbed. Tests are determined according to ČSN P CEN/TS 15210-1 for pellets and ČSN P CEN/TS 15210-2 for briquettes. Mechanical resistance should not be lower than 90% (Kotlánová, 2010).

- **Strength**

Strength of pressed biofuels is secured by content of lignin in biomass. Lignin acts as a binder and forms protective binder on the surface of biofuel (Janíček, 2011). During pressing is released ammount of heat which activated (plasticizated) lignin. Fast cooling behind the die of pellet mill pellets gain typical strength and shiny surface which is resistant against humidity (Lyčka, 2011).

2.3. Straw as a biofuel

Straw is usually known as a by-product from cereal especially in areas with production of winter wheat (*Triticum aestivum* L.) and other cereal species. In Czech republic the straw has traditionally been used for fodder and bedding in animal production, but in present considerable part of straw production stays unutillized in stacks on the fields, where is gradually destructed, mainly by weather conditions. This is due to high share of cereals on the arable land, increasing use of slatted floors in housing systems for cattle and decreasing of cattle breeding (Larsen *et* al., 2012) and (Kára, 2003). Since the 1990 in CR decreased number of cattle by about 60% (Abrham *et* al., 2012). Straw has also other posibillities of use such as incorporation into the soil which builds up soil carbon, soil nitrogen and returns valuable nutrients to the ecosystem (Nguyen et al., 2013). For this reason is recently a large part of production incorporated back to the soil but it has also other effects. Straw contains usually less than 1% of nitrogen and bacterias which decomposes the straw take nitrogen from the soil. Therefore is necesssary to add nutrients in the form slurry or anorganic fertilizers (Abrham *et* al., 2012). Since the late nineteenth century straw in bales has been also used as construction material and isolation for buildings (Carfrae *et* al., 2011). During the first decade of the 21st century increased the attention on renewable energy sources due to highly unstable energy prices and the use of straw for energy production has been in the interest again (Gauder *et* al., 2011).

2.3.1. Utilization of straw

Utilization of straw is moving from exclusively agricultural production to the sphere of energy and construction industry. Straw for energy purposes can be utilized as an additive in heat powerplants or in boiler rooms as a raw material, in the form of briquettes or pellets and also in special boilers as a straw bales (Pražan *et* al., 2007). By combustion of straw in local heating plants can be decreased dependence on natural gas and also stabilized the prize of heat for customers (Voláková, 2010). According to Abrham *et* al., (2003) is possible to use 25-33% of harvested straw without influence on soil fertility. In CR it is producted about 6 – 6.5 mil. tons of grain and oil plant straw from which it can be used for energy purposes about 4 mil. tons per year. Straw has advantage in contrast to other renewable sources that its production is relatively constant and can be stored and used in the time of demand (Abrham *et* al., 2012) and (Voláková, 2010).

The table (Annex 1) shows that on the largest area is planted winter wheat *(Triticum aestivum)* which was grown in 2010 on the area about 785491 ha with total yield of straw 37703657 t at average 4.8 $t*ha^{-1}$. From the table it is also noticeable increasing area of rapeseed which becomes popular due to higher demand on the liquid biofuel market (biodiesel). Rapeseed straw is not used for biodiesel production or in animal husbandry also is not suitable for incorporation back to the soil and its potential for solid biofuels is higher than cereal straw. In the CR there is a total of 4347000 tons of cereal and rape straw usable for energy at 50% utilization (Abrham *et* al., 2012).

Table 8.: Straw production for energy utilization in the CR

	Straw production (t)	**Energy potential (GJ)**
Wheat	1994162	29912000
Rye	69766	1046000
Barley	690368	10356000
Oat	77870	1168000
Corn for grain	250485	3757000
Other cereals	82469	1237000
Rapeseed	1103070	16546000
Total	**4268190**	**64023000**

Source: Abrham, (2012)

Available energy potential in the CR is about 64 TJ which is from almost 50% created by wheat straw and about 15% created by rapeseed straw. According to Abrham et al. (2012) the biggest producent of wheat and rapeseed straw is Central Bohemia Region with energy potential about 30 TJ. Biofuels from straw are energetically and economically suitable source of energy and presents suitable alternative to fossil fuels. Straw utilization does not influence food security or soil fertility. Costs for straw production are in all types of processing lower than price of coal and in the case of straw bales are costs about 30% lower than energy coal. Energy utilization of residual biomass presents for farmers possibility of energy securing from own resources and also diversification of business activities. There other advantages such as positive influence on landscape and environment, creating of new job opportunities and also increase of economic and energy stability of farms (Abrham *et* al., 2012).

2.3.2. Types of straw biofuels

As a material can be considered straw of cerals and oil crops, grasses and energy herbs such as hemp *(Canabis)*, *Miscanthus giganteus* or Japanese knotweed *(Fallopia japonica)*. The lower bulk density is characteristic for biofuels which can cause problems with manipulation and increase costs for transport. Bulk density of chopped straw is about 40 kg*m^{-3} in contrast to pellets which can reach 1200 kg*m^{-3}. Due to lower bulk density and also requirements of combustion equipments is straw ussually processed to a more suitable form (Andert *et* al., 2006).

Andert *et* al., (2006) presents three forms of processed straw as a biofuel:

- Straw bales
- Straw briquettes
- Straw pellets**Straw bales**

Straw is usually transported from the field in a form of bales. According to shape are distinguished cylindrical, square or rectangular bales. Bulk density depends on the construction of press equipment and on particle size of material. Straw bales can be described as a solid biofuel according to the ČSN P CEN/TS 14961 (5) (Hutla, 2010). According to Andert *et* al., (2006) are utilized low-pressure bales with density about 60 kg*m^{-3} and weight between 3 - 10 kg. High-pressure bales with density about 120 kg*m^{-3} and weight 10 - 20 kg. Giant cylindrical bales with density about 110 kg*m^{-3}and weight 200 - 300 kg and also giant prism bales with highest density about 150 kg*m^{-3} and weight 300 - 500 kg. According to requirements of boiler house contractor must observe agreed parameters of bales (Andert *et* al., 2006). Straw bales are cheap source of energy which is suitable for combustion in industrial boiler houses with efficiency above 250 kW. These boilers are not determined for heating of family houses but for larger buildings such as farms or industrial hall. Straw is most often supplied in a form of giant prism bales wich can combined also with wood chips, hay or energy plants (Stupavský, 2010).

- **Straw briquuettes**

Straw briquettes are mechnically under high pressure pressed dry and crushed or chopped stalk plants such as straw of cereals and oilseeds, grasses or energy herbs with moisture content up to 14%. Shapes of briquettes can be different according to type of press equipment. On the market are common briquettes in shape cylindrical, prismatic or hexagon with the same parameters as wood briquettes. In the case of oilseed straw can calorific value reaches 19 $MJ*kg^{-1}$. In contrast to wood briquettes the straw ones have got higher ash content about 5 - 6%. These briquettes are often pressed with additives which are specified by standards (Andert *et* al., 2006). With higher density in contrast to straw bales are briquettes more suitable for manipulation, transport and storage. Briquettes are ussally used in boilers, stoves or fireplaces with hand stoking and heat output above 25 kW (Piszczalka, 2012).

- **Straw pellets**

The importance of fuel pellets made from other than wood biomass is increasing. Especially in agriculture where the intenzification and reduction of livestock production caused that is produced high ammount of residues whithout utilization. One of the posibillities is to use these residues for pellets production (Hjuler, 2007). Heating with straw pellets has potentional especially in private home heating where can be saved about 25 - 30% of costs according to wood pellets. Advantage of pellets in contrast to briquettes is larger surface area allowing better process during combustion and also automatization of stoking to the boiler (Slavík *et* al., 2006).

Pellets production is relatively complicated and energy challenging process therefore is necesary to know requirements and properties of pressing machine and pressed material because it is not effective to make a fuel with higher energy consumtion than is its own energy value (Kott, 2010).

- *Moisture content*

According to Theerarattananoon *et* al., (2011) the feedstock must have optimum moisture content to produce stable and durable pellets. For pelletized biomass is ussually recommended optimum moister content 8 - 12%. Feedstock with higher moister content decrease long-term quality of pellets which begin crumble after time and also significantly affects calorific value (Kott, 2010; Kotlánová, 2009). Moisture content of straw depends on weather conditions during harvest and on storage conditions. By influencing of these operations can be decreased MC wihout additional drying which significantly increase costs (Raila *et* al., 2012). Theerarattananoon *et* al., (2011) researched effect of moisture content on density and durability of pellets made from straw (corn stove, wheat straw, sorghum straw, big bluestem straw). With increasing moisture level decreased bulk and true density of all types tested pellets. Durability of pellets from wheat straw and corn stover was not affected at moisture content between 9 - 14% but at MC above 14 % was durability significantly reduced. Big bluestem pellets have similar values but with highest durability between 9 - 11% of moisture content in contrast to sorghum pellets which reached maximum values of durability (89.5%) between 14 - 16% of moisture content. Raila *et* al. (2012) compared influence of MC on electric energy consumption by press and its capacity. During pelleting wheat straw with 17.2% moisture was consumed 157 kWh of electric energy and capacity of press was approximately 0.55 $t*h^{-1}$. In contrast to pelleting straw of MC 13.15% was consumed 138.93 kWh of electric energy and capacity was 1.2 $t*h^{-1}$. This is due to resistance of wet straw to tearing which must be compensated by higher energy input.

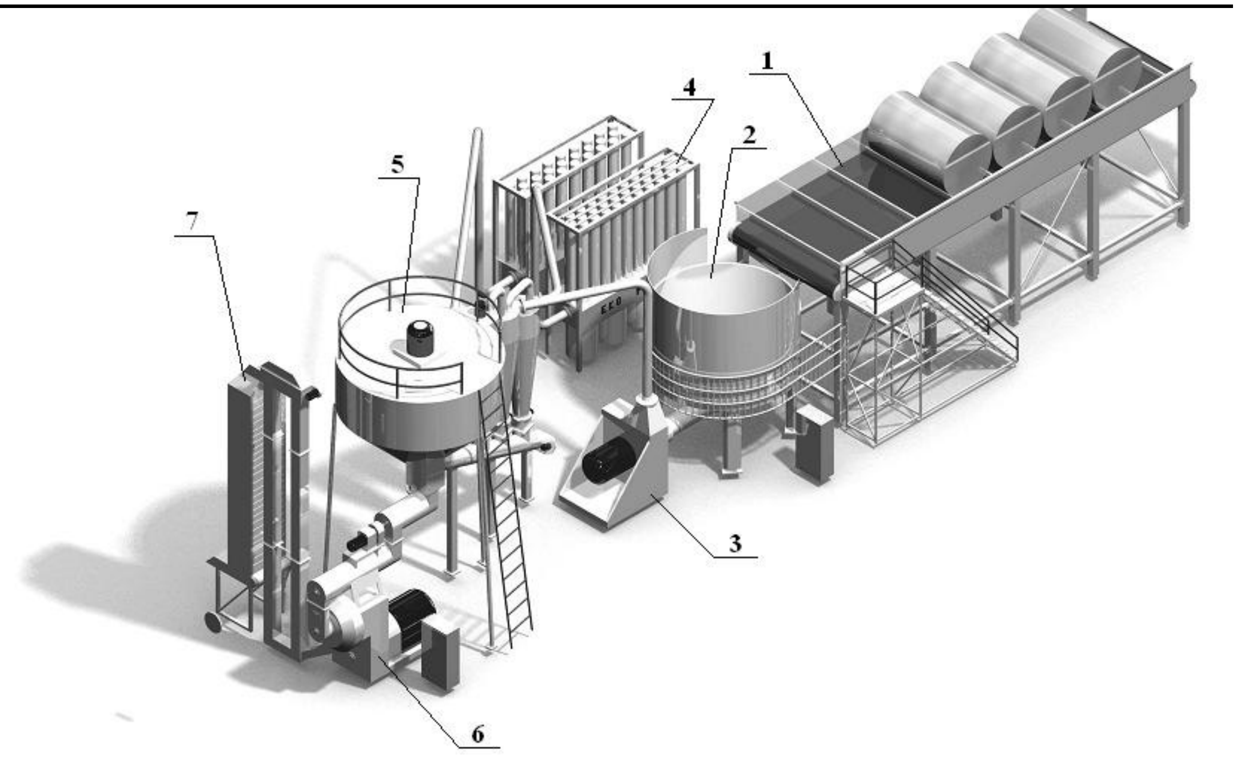
- *Particle size of pressed material*

According to Kott (2010) particle size of material should not exceed 1/5 of diameter of final pellets. With finer structure of material is increased final strength because of larger surface area of particles which can be connected. Usually is material shredded on the sives with openings 4 - 6 mm. Briquette and pellet presses have got high requirements on particle size of input material. Required particle size can be reached by mechanical treatments such as shredding. Advantage of these operations is in simplification of manipulation and in easier assessment properties of material on the other these treatments are energy-consuming (Souček *et* al., 2003).

- *Pelleting*

Comercial granulation of straw and similar materials in CR is done on press with capacity 1 - 6 $t*h^{-1}$. Also exist presses with capacity about 15 $t*h^{-1}$ but these presses are used in large industrial centers and in Europe it is not usual. Hutla, (2010) mentions two pellet presses available in CR. Pellet press LSP 1800 m from company Atea Praha with capacity 1.5 - 1.8 t*h^{-1} and can process 10000 tons of straw per year. Other possibility is press MGL 200 from company Kovo Novák. This press is determined especially local use and small consumers. MGL 200 with flat die can produce straw pellets with efficiency 100 kg*h^{-1} (Hutla, 2010). Material is usually transported to the pelleting press by screw coveyor and is steamed or moisturized by water. According to Kott (2010) is more suitable to use steam especially in the case of straw. It is recommended to use pressing system with ring die and two pressing rollers. Advantage is high pressure, easy feeding of material to the rollers and uniform load on whole area of die (Kott, 2010). Theerarattananoon *et* al., (2011) compared effect of die size on durability of pellets. According to results use of thicker die (44.5 mm instead of 31.8 mm die thickness) have significant impact to pellet durability and also bulk density. With thicker die increase durability of pellets made from wheat straw, corn stover and from sorghum stalks. After leaving the die of press are granules soft and sticky and must be cooled immidiately after leaving the press. Cooled pellets are separated from crumbles which are transported back to the press (Kott, 2010).

Figure 2.: Radviliškis Machine factory, ŠSGL – 1



Source: Raila, (2012)

Technological line for straw pelleting: 1 – conveyor, 2 – shredder, 3 – mill, 4 – air cleaning system, 5 – hopper for chopped material, 6 – pelleting press, 7 – cooler.

2.3.3. Problem aspects of straw utilization

Straw is cheap source of energy in compare to fossil fuels but also to wood fuels. On the other hand combustion of straw is relatively difficult due to specific chemical compostition (Voláková, 2010). Combustion of stalk plants is much more complicated than wood due to higher requirements on fuel processing, storage, manipulation and also on filtration of flue gas and ash. In smaller furnaces should be used stalk plants in presssed form (briquettes, pellets) in contrast to large boiler rooms where can be combusted bales or straw in chopped form together with wood or coal (Andert *et* al., 2006).

- **Corossion**

In large furnaces is direct combustion almost perfect but with temperatures above 600°C which is necessary for correct combustion of flue gasses is starting to show agression of chlorine which is contented in straw. Chlorine is transformed to HCl which affects corrosion on metal heat exchangers. It requires special measures and also stainles steel materials. Denmark heating plants decrease corrosin effect by adding limestone into system of fluidised bed combustion and also common combustion of straw with coal (Andert *et* al., 2006).

- **Ash sintering**

The straw ash contains alkali metals, metals of alkali soils and silicon. The content of elements is similar to mixtures for production of glass. It caused formation of slag and during higher temperatures can be formated enamel which disrupts lining surfaces of the boiler body. For this reason is necessary to relatively often interrupt working boiler during the heating season and clean problem parts (Voláková, 2010). Use of rapeseed straw for combustion does not affect problems because rapeseed straw have similar ash sintering temperatures as wood. Cereal straw has lower sintering temperatures which can be increase by adding of crushed brown coal. Hutla, (2010) also states that by adding hulls of cacao beans into wheat straw pellets increase fusing temperature on 900 °C.

- **NO_x emissions**

During combustion nitrogen contained in straw and nitrogen in air form undesirable NO_x emissions. Andert *et* al., (2006) states that up to the content 1.5% is possible to limit these emissions if are not exceeded temperatures above1100 - 1200 °C. Wheat usually contain about 1,25% of nitrogen but meadow hay can contain 1.8% and alfalfa can have more than 2.8%.

According to Andert *et* al., (2006) is advantageous to let the stalk plants leach on the field. It leached for combustion undesirable substances which can be beneficial for soil. By leaching can be decreased N content in wheat straw from 1.5% to 0.5%.

III. HYPOTHESIS AND OBJECTIVES

3.1. Hypothesis

The hypothesis for this BSc. Thesis were formulated on basis of reference analysis and own experience gained during previous activities in the field of solid biofuel testing. They are as follows:

1. With increasing percentage of coal dust additive the pellet calorific value increases too;
2. The increasing percentage of coal dust additive influences negatively the pellet mechanical durability.

3.2. Objectives

The overall (main) Thesis objective is ecologic and effective use of brown coal dust mixed up with wheat straw in the form of pellets, their testing and optimum formulation selection.

Specific Thesis objectives can be formulated as follows:

1. Working out couple of formulations of pellets as mixture "ground straw with brown coal dust";
2. Testing pellets produced according to formulated compositions;
3. Selecting optimum pellet formulation on basis of testing its calorific value and mechanical durability.

IV. METHODOLOGY

4.1. Materials

The main raw material (chopped wheat straw) was delivered by ATEA PRAHA, s.r.o. Brown coal dust is formed during transport and manipulation with brown coal briquettes Heizprofi. Dust was prvovided by company MB AUTODOPRAVA. Briquettes are produced from brown coal sludge which is mined in Germany in the area between Aachen, Düsseldorf and Köln where are found the biggest deposits of brown coal in Europe. Heizprofi briquettes are made from dried brown coal sludge without binders and additives by pressing.

4.2. Grinding of the raw material

Chopped wheat straw was ground using a hammer mill type 9FQ - 40C (Pest Control Corporation). Straw was ground with hammer mill screen size 3.8 mm. Figure 3 shows hammer mill 9FQ - 40C.

Figure 3.: Hammer mill 9FQ – 40C

Source: Ondřej Novotný, (2012)

4.3. Mixing of the raw material

The raw materials were weighted and mixed in three different ratios. Brown coal dust was sieved on a sieve screen with holes of 4 mm size. Mixtures were prepared in percentage ratios (straw : dust): 95:5; 90:10; 80:20. For mixing was used universal mixer borrowed from VÚZT which is shown on the Figure 4.

Figure 4.: Universal mixer with sample

Source: Ondřej Novotný, (2012)

4.4. Pelleting

Created mixtures were pelleted on the granulating line model MGL 200 borrowed by VÚZT, v.v.i. Praha which is shown on the Figure 5. The line consists from supply auger, dosing device, mixer, granulator and cooling and sorting device. Own granulator consists from flat die with 8 mm hole openings and rollers which is shown on the Figure 6. Pellets produced in three different ratios of materials are shown in the Figure 7.

Figure 5.: Granuling line model MGL 200

Source: Ondřej Novotný, (2012)

Figure 6.: Detail of flat die with rollers

Source: Ondřej Novotný, (2012)

Figure 7.: Produced pellets

Source: Ondřej Novotný, (2012)

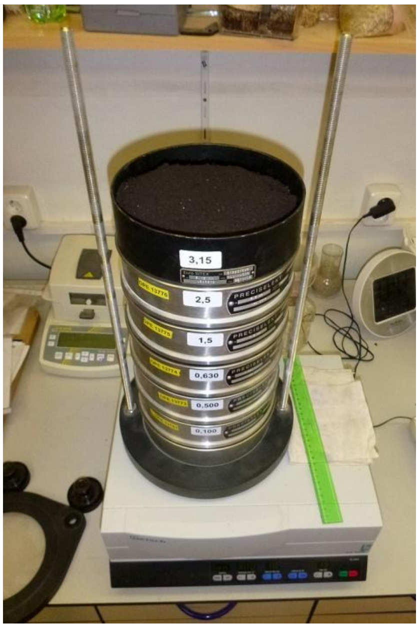
4.5. Specification of physical and mechanical properties

4.5.1. Determination of the size distribution of particles

Size distribution of particles of ground wheat straw and brown coal dust was determined according to ČSN P CEN/TS 15149-1. The sieve shaker Retsch AS 200 which is shown on the Figure 8 was used to perform the experiments. The sieve shaker is equipped with timer and possibility of setting the amplitude.

The determination principle: For determination were used six sieves with different size of the hole openings (0.100; 0.500; 0.630; 1.5; 2.5; 3.15 mm). From each material (ground wheat straw and brown coal dust) were weighted three samples and tested. Each sample was shaked for 15 minutes with 10 seconds interval and with amplitude 3 mm. After shaking was weighted material on the sieves and calculated percentage ratio of individual fractions

Figure 8.: Sieve shaker Retsch AS 200 with sample of brown coal dust



Source: Ondřej Novotný, (2012)

4.5.2. Determination of moisture content

Moisture content of raw material was determined according to ČSN P CEN/TS 14774-1 (-2, -3). For determination was used drying oven Memmert model 100 - 800 equipped with timer and volume of the chamber about 100 dm^3. The drying oven is shown on the Figure 9 and Figure 10.

The principle of determination: The samples were putted in beakers and weighted on laboratory scale. Samples in beakers were placed into the drying oven and for about 5-8 hours at temperature 105 °C. After drying were beakers with samples cooled for about 20 minutes and weighted. The moisture content was calculated by simple formula (2):

$$\mathbf{w=[(m_w-m_d)/\ m_w]*100=\ \%} \qquad (2)$$

where: $\mathbf{m_w}$**-** weight of wet sample before drying (g)

$\mathbf{m_d}$**-** weight of dried sample

Figure 9.: Drying Memmert with samples

Source: Ondřej Novotný, (2012)

Figure 10.: Detail of samples in drying chamber

Source: Ondřej Novotný, (2012)

4.5.3. Determination of calorific value

Calorific value of produced pellets was determined as calorific value of both raw materials and than calculated according to the standard ČSN EN 14918. For determination was used automatic calorimeter Laget MS-10A with accessories (shown on the Figure 11).

The principle of determination: The calorific value was determined in a bomb calorimeter. Samples of dried and weighted material were burned in the oxygen atmosphere in a stainless steel high-pressure vessel (bomb). The vessel with sample was placed in a calorimeter which contains a known volume of water with a known temperature. The combustion products CO_2 and H_2O are allowed to cool to the standard temperature. The result heat of combustion is measured from the accurate measurement of the rise in the temperature of water in the calorimeter, the calorimeter itself and the vessel (Ivanova, 2012). This way determined calorific value is the gross calorific value **(Q_{gr})** which is calculated according to the formula (3):

$$\mathbf{Q_{gr} = (dT_k.T_k - (c_1+c_2))/m} \ (J.g^{-1}) \qquad (3)$$

where: $\mathbf{dT_k}$ – temperature jump (°C)

$\mathbf{T_k}$ – heat capacity of calorimeter = 9161 J

$\mathbf{c_1}$ – repair of benzoic acid= 20 J

$\mathbf{c_2}$ – repair of the heat released by burning spark fine wire = 70 J

m – weight of material sample (g)

Net calorific value is calculated according to formula (4):

$$\mathbf{Q_i = Q - 24{,}42.(w+8{,}94.H^a)} \ (J.g^{-1}) \qquad (4)$$

where: **Q** – heat of combustion ($J.kg^{-1}$)

24.42 – coefficient corresponding to 1% of the water from the sample at 25 ° C ($J.kg^{-1}$)

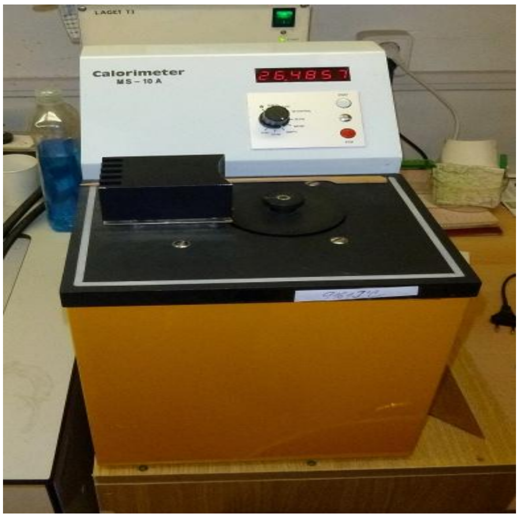
w – water content in the sample (%)

8.94 – coefficient for the conversion of hydrogen to water

$\mathbf{H^a}$ – hydrogen content in the sample

For calculation of net calorific value was used value of average hydrogen content in biomass (6%) and for brown coal dust was used average value of hydrogen content (5.5%) according to ČEZ.

Figure 11.: Calorimeter Laget MS – 10A



Source: Ondřej Novotný, (2012)

4.5.4. Determination of mechanical durability

Mechanical durability of final pellets was determined according to ČSN EN 15210-1 on device Ligno-tester provided by VÚZT, v.v.i. Praha which is shown on Figure 12. Each sample of pellets was tested 5 times.

The principle of determination: Sample of pellets was weighted and placed into the chamber of Ligno-tester where are set in motion by airflow for 1 minute. Pellets hit each other and to the walls of chamber it caused abrasion. After removing from chamber the pellets were again weighted and weight losses was monitored. Mechanical durability was calculated according to formula (5):

$$D_U = m_A/m_B*100\ [\%] \qquad (5)$$

where: m_A- weight of pellets after testing (g)

m_B- weight of pellets before testing (g)

Figure 12.: Ligno - tester

Source: Ondřej Novotný, (2012)

4.5.5. Experimental data processing

1. Statistical processing

The experimental data were processed by tools of basic statistics, results of which average values, standard deviation, etc. have been put into the table.

2. Results formulation

The experimental results and their processed characteristics were graphically processed, put into figures and discussed in the chapter 4.

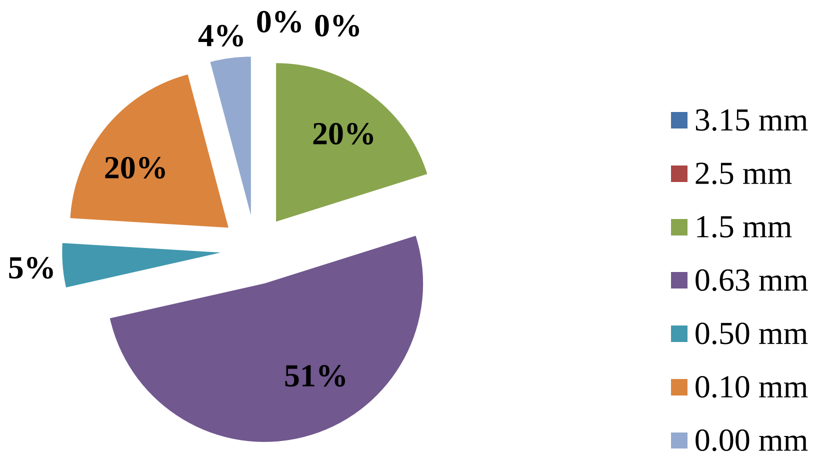
3. Conclusion and recommendation formulation

After the results having been properly processed and discussed the conclusions and recommendations were formulated and put into the chapter 4. First conclusions on hypotheses were produced whereby the individual hypotheses were either confirmed or refused. Following other conclusions were formulated from all chapters of the Thesis. On the basis of conclusions three recommendations have been formulated as for solid biofuel producers as well as consumers.

V. RESULTS AND DISCUSSION

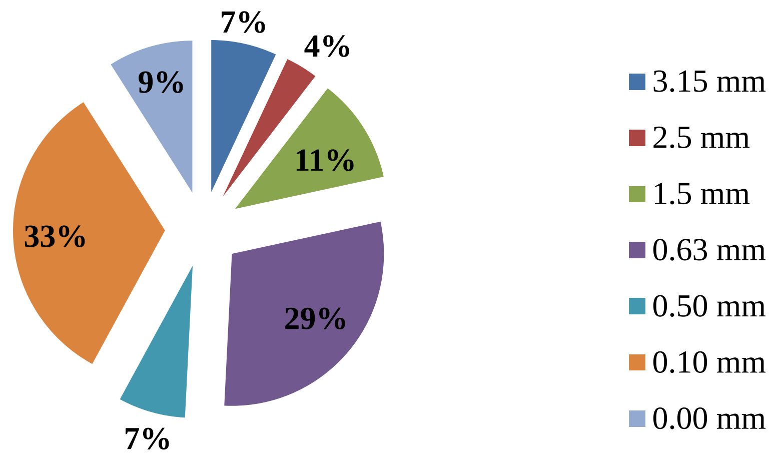
5.1. Distribution of particles

Figure 13.: Particle size of ground wheat straw



Source: Ondřej Novotný, (2012)

Figure 14.: Particle size of brown coal dust



Source: Ondřej Novotný, (2012)

The Figure 13 shows that the highest ammount of ground wheat straw (about 51%) was captured on the sieve with screen size openings 0.630 mm in contrast to the sieves of screen size 3.15 mm and 2.5 mm where was not captured any straw. Wheat straw which was ground in hammer mill with screen size 3.8 mm contains mainly particles of size between 0.630 mm and 1.5 mm. Figure 14 shows that the highest ammount of brown coal dust was captured on the sieves 0.100 mm (about 33%) and 0.630 mm (about 29%). Least of the coal dust was captured on the sieve with screen size openings 2.5 mm. Brown coal dust contains mainly particles of size between 0.100 mm and 0.500 mm and also about 29% of particles between 0.630 mm and 1.5 mm.

5.2. Moisture content

Moisture content was determined as average moisture content from three samples of chopped wheat straw and three samples of brown coal dust. Chopped wheat straw had average moisture content 8.01% and brown coal dust 20.28%. All input mixtures prepared for pelletizing had suitable moisture content below 12%.

5.3. Calorific value

Measured and statistically processed gross calorific values of raw materials are shown in the Table 9 :

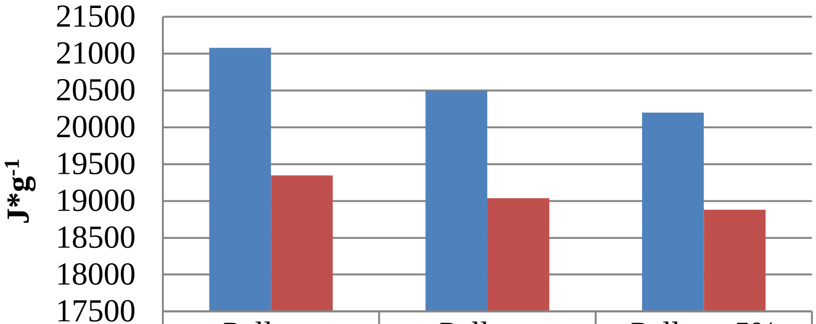
Table 9.: Average gross calorific values of raw materials

	Straw		**Coal**	
	Q-lm	**Q-d**	**Q-lm**	**Q-d**
	19140,2	19876,2	21712,1	25837,2
	18392,0	19929,9	22206,9	25584,7
	18648,0	19916,2	21587,9	25865,9
Average	**18726,7**	**19907,4**	**21835,6**	**25762,6**
SD	**380,3**	**27,9**	**327,5**	**154,7**

Source: Ondřej Novotný, (2012)

The Table 9 shows that average gross calorific value of straw with laboratory moisture content was 18726.7 $J*g^{-1}$ ± 380.3 $J*g^{-1}$ and for dry straw was 19907.4 $J*g^{-1}$ ± 27.9 $J*g^{-1}$. Gross calorific value of brown coal dust with laboratory moisture content was 21835.6 $J*g^{-1}$ ± 327.5 $J*g^{-1}$ and for dry coal was 25762.6 $J*g^{-1}$ ± 154.7 $J*g^{-1}$.

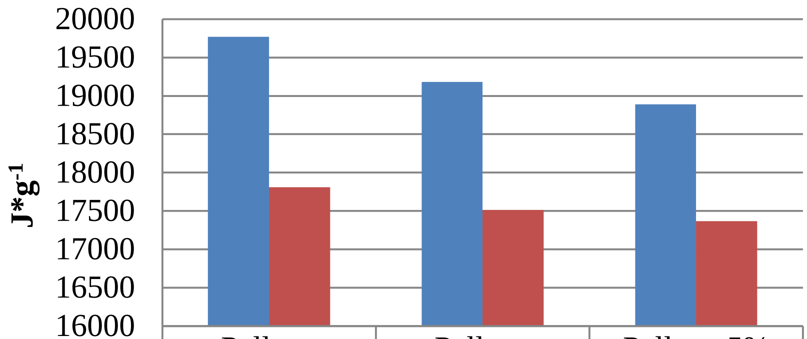
Figure 15.: Gross caloric value of pellets



	Pellets- 20% coal	Pellets- 10% coal	Pellets- 5% coal
Q- dry matter (J/g)	21078,47	20492,95	20200,19
Q- laboratory moisture (J/g)	19348,48	19037,59	18882,15

Source: Ondřej Novotný, (2012)

Figure 16.: Net calorific value of pellets



	Pellets- 20% coal	Pellets- 10% coal	Pellets- 5% coal
Qi- dry matter (J/g)	19768,58	19183,06	18890,300
Qi- laboratory moisture (J/g)	17807,4	17514,31	17367,76

Source: Ondřej Novotný, (2012)

Both figures show that incresing ratio of brown coal dust in wheat straw pellets increases their GCV and NCV. With 5% coal additive was average GCV of pellets in laboratory moisture 18882.15 J*g^{-1} while with 20% of additive it was 19348.48 J*g^{-1}. With increase of 15% coal additive GCV increased by almost 0.5 MJ*kg^{-1}. For practical use it is more important NCV because GCV is determined in laboratory conditions which can not be achieved in usual boilers or stoves. NCV for pellets with 5% of coal additive in laboratory moisture is 17367.76 J*g^{-1}. It is about 1747 J*g^{-1} higher than in the case of pure wheat straw pellets GRANOFYT S produced by company ATEA Praha s.r.o. and almost the same value as in the case of DIN*plus* certified wood pellets (17.38 MJ*kg^{-1}) according to Verma *et* al. (2012). Jevič *et* al. (2007) compared NCV of wheat straw briquettes with 5% and 20% of brown coal. In the case of briquettes with 20% of brown coal was NCV higher about 0.54 MJ*kg^{-1} than in the case of 5% briquettes. In compare with producted pellets is increase of NCV similar. Pellets with with 20% of brown coal dust have higher NCV about 0.44 MJ*kg^{-1} than pellets with 5% of coal dust. Best results from the viewpoint of NCV have pellets with 20% brown coal dust 17807.4 J*g^{-1} which is comparable to pellets made from wood of *Bowdichia nitida* which have NCV 17907.85 J*g^{-1} (Telmo *et* al., 2011).

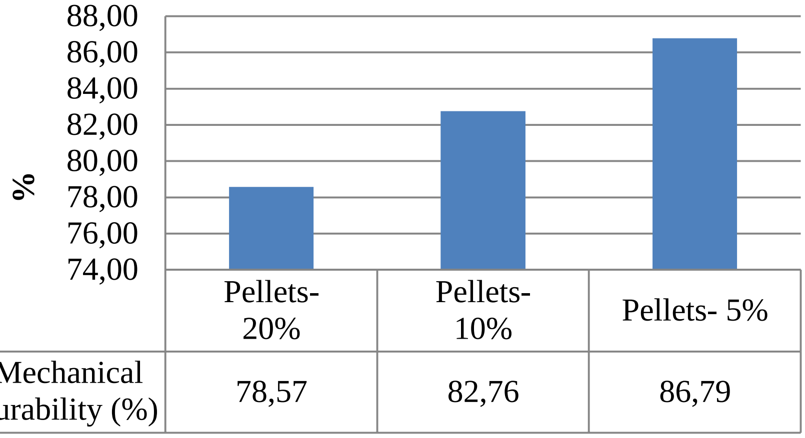
5.4. Mechanical durability

Table 10.: Average mechanical durability of produced pellets

	Pellets – 20%	**Pellets – 10%**	**Pellets – 5%**
	80,1%	84,1%	86,7%
	80,6%	78,7%	85,7%
	78,0%	85,0%	86,7%
	73,7%	82,8%	89,5%
	80,4%	83,1%	85,4%
Average (%)	**78,6**	**82,8**	**86,8**
SD (%)	**2,9**	**2,4**	**1,6**

In the Table 10 are shown average values of mechanical durability with standard deviation for each type of tested pellets.

Figure 17.: Mechanical durability of produced pellets



Source: Ondřej Novotný, (2012)

With encreasing ammount of brown coal additive in pellets decrease their mechanical durability. In the Figure 17 is shown that for pellets with 5% of coal additive was detected highest durability 86.79% ± 1.6% from tested samples. In pellets with 20% of additive was detected lowest durability 78.57% ± 2.9%.

According to Theerarattananoon *et* al. (2010) 5% and 10% pellets can be considered as high durable and 20% pellets as medium durable. Theerarattananoon *et* al. (2010) also tested influence of hammer mill screen size and die thickness on durability of pure straw pellets. When was wheat straw ground on hammer mill screen size 6.5 mm instead of 3.2 mm durability of pellets was higher about 1%. In the case of our pellets was used hammer mill screen size 3.8 which could cause lower mechnical durability. Also thickness of die influences durability because on 41.5 mm die were produced pellets about 2% more durable than on 31.8 mm die (Theerarattananoon *et* al., 2010). Moisture content of input material could affect durability of final pellets which was relatively low. Moisture content of mixtures for pelleting ranged between 8-12% while in pure straw pellets produced by ATEA Praha s.r.o. was determined moisture content 6.4% and mechanical durability almost 99%. During pelleting was apparent fluctuating temperature of granulator (die). Larsson *et* al. (2011) examined effect of die temperature on durability of pellets made from reed canary grass. Ideal die temperature for pelletizing was determined in the range 30-45 °C. Within this temperature range was the most beneficial low die temperature when was produced pellets with high mechanical durability. According to ČSN EN 14961-1 can be produced pellets classified in category DU95.0- where are classified pellets with mechanical durability lower than 95%. Mechanical durability of produced pellets could be affect by many parameters such as moisture content and particle size of input material, thickness and temperature of die or by using water for wetting instead of steam.

5.5 Selecting optimum pellet formulation

On the basis of produced pellets testing was selected an optimum formulation which would satisfy potential producer and consumer by both its NCV and mechanical durability.

The selection is a compromise between calorific value which grows along with increasing brown coal contents and mechanical durability which, under the same conditions, decreases. The following Figures 16. and 17. shows both of two main criteria. As the best option from tested types of pellets can be considered pellets with 10% of coal additive. From the viewpoint of calorific value and mechanical durability these pellets show the medium values from both tested criteria.

VI. CONCLUSSIONS AND RECCOMENDATIONS

On basis of reference analysis and experimental data with discussion the following conclusions can be formulated. They are especially on hypotheses which had been formulated as the first Thesis structural elements.

6.1 Conclussions

1. The first hypothesis *„With increasing percentage of coal dust additive the pellet calorific value increases too“* can be confirmed; it is on basis of experimental data (testing the calorific value of pellet raw materials). It is because the coal has got higher calorific value than straw - with its growing percentage in the pellet the overall pellet calorific value increases, too.

2. The second hypothesis „*The increasing percentage of coal dust additive influences negatively the pellet mechanical durability*„ can also be confirmed. It is because the coal dust hinders firm bindings between straw particles and it is not a good gluing element to establish good physical bindings between coal particles.

3. The wheat straw is a suitable raw material for biopellet production which is relatively abundant, cheap and accessible.

4. According to what was found in the literature the mechanical durability of pellets can be influenced by many other measures such as particle size of raw material, thickness and temperature of die in granulator, moisture content of material or wetting material by steam instead of water. These factors were not specifically surveyed by the present experimental testing but can be assumed as the matter of fact.

5. According to the testing results the optimum pellet formulation has been selected. After assessment of both selection criteria (Net Calorific Value and Mechanical Durability) courses of which as dependent on brown coal contents are in opposition, the optimum pellet composition (wheat straw + brown coal) has been proposed the mixure of 90% of straw and 10% of brown coal. However, some future emission tests must be conducted to create a base for whether the pellets satisfy all the requirements of relevant standards.

6.2 Recommendations

1. From the viewpoint of heating values and also low prices of wheat straw and brown coal dust these materials can be reccomended for production of pellets. The optimum mixture composition is wheat straw pellets with 10% of coal additive. However, the emission tests must be conducted to complete information on mixed pellet properties for reason of decision making on whether the proposed composition satisfies all the requirements given by relevant standards.

2. It is recomended to continue in examining impacts of particle size of material, methods of wetting or temperature of die in granulator on mechanical durability of final pellets. This recommendation is given for reason of considering the above factors but not examining them for a limited time and budget of the present Thesis.

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VIII. ANNEXES

Annex 1.: Straw yelds in CR

		2000	2005	2008	2009	2010	Straw yield	
Crop	**Units**						**t/ha**	**Total (th. tons)**
Winter wheat	Area (ha)	886 562	762 792	760 399	793 472	785 491	4,8	3743
	Gr. yield (t/ha)	4,34	5,15	5,88	5,33	5,08		
Other cereals	Area (ha)	43 661	72 968	67 651	61 818	54 531	3,1	190
	Gr. yield (t/ha)	3,46	3,68	3,99	3,84	3,35		
All cereals	Area (ha)	1 690	1 651	1 581	1 571	1 494	3,9	6532
	Gr. yield (t/ha)	3,87	4,7	5,32	5,03	4,64		
Rapeseed	Area (ha)	323 842	267 160	356 924	354 826	368 824	6	2161
	Gr. yield (t/ha)	2,61	2,88	2,94	3,18	2,83		
Usable straw of cereals and rapeseed			**Cereal straw (50%)**					3266
			Rapeseed straw (50%)					1081
			Total					4347

Source: Abrham et al., (2012)