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SOLID RECOVERED FUELS FROM AGRICULTURAL WASTES

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ABSTRACT: Solid recovered fuels are fuels produced directly or indirectly from the biomass. Main goal of this work is to analyze some selected solid recovered fuels from agricultural wastes which were in form of briquettes. They were analyzed in order to find out chemical and stoichiometric composition and energy balance. Technical standard ČSN EN 13229 "Inset appliances for heating including open fires fired by solid fuels – Requirements and test methods" was performed to determine the basic assessment of thermal efficiency and emission parameters. A prototype of combustion accumulation stove SK-2 (nominal heat output of 8 kW) was used. Tested materials were the bio-briquettes with a diameter 65 mm from mixture of fermented mixture 33 % (rotten fermented waste treatment slurry) and 67 % wood ships, cereals cleaning residues, mixture of cereals cleaning residues and meadow grass in a ratio 1:1 and mixture of cereals cleaning residues and energy sorrel in a ratio 1:1.
Key Words: Solid alternative - recovered fuels, bio-fuel, stoichiometric calculations, emissions and energy parameters

TARIMSAL ATIKLARDAN ELDE EDİLEN KATI YAKITLAR

ÖZET: Doğrudan veya dolaylı olarak biokütleden elde edilen yakıtlara yeniden elde edilen katı yakıtlar denilmektedir. Bu çalışmanın ana amacı tarımsal atıklardan elde edilen briket haline getirilmiş seçilmiş bazı katı yakıtları incelemektir. Katı yakıtların kimyasal ve stokiyometrik kompozisyonları ile enerji dengeleri incelenmiştir. Isısal verim ve emisyon parametrelerinin belirlenmesinde ČSN EN 13229 (Katı yakıtlarla yakılan açık yanmaları da kapsayan ısısal donanımlar, araç ve gereçler – Gerekli şartlar ve test yöntemleri) teknik standartları esas alınmıştır. Denemelerde yoğuşmalı yanmalı bir soba prototipi (8 kW) SK-2 kullanılmıştır. Denemelerde kullanılan katı yakıtlar 65 mm çapında bio-briketlerdir. Bunlar; % 33 bozulmuş atık maya bulamacı ile % 67 odun talaşı karışımı, tahıl temizleme atıkları, 1:1 oranında karıştırılmış tahıl temizleme atıkları ile çayır ve 1:1 oranında karıştırılmış tahıl temizleme atıkları ve kanarya otundan oluşan mayalanmış karışımlardır.
Anahtar Kelimeler: Alternatif katı yakıtlar, bio-yakıt, stokiyometrik hesaplamalar, emisyon ve enerji parametreleri

1. INTRODUCTION

Solid recovered fuels (SRF) have worldwide importance due to of rapid increase of fuels use, renewable energy sources and biomass. The solution will bring a definite classification and specific principles of agricultural wastes use. Classification and specification provides them acceptability at the fuels market and public confidence increase. It also precipitates compulsory approval procedures, information exchange about solid biofuels use ad alternative fuels from renewable sources and connected environmental problems.

The share of energy from renewable resources should reach the level of 30 % of total energy consumption within 50 years. The share of energy from renewable resources should be raised from current 6 % to 12 % in the countries of EU in the year of 2010. The biomass share of the renewable energy sources is currently about 60 % and its growth to the share of 80 % is expected. It is planned to alter one fifth of the fuel consumption by alternative fuels in EU. It will reduce the crude oil supply dependency and will lead to the improving of atmosphere quality (Directive 2001/77/EC, 2001; Olson, 2006).

The increasing of renewable energy sources became the priority of 6th general program in the area of energetic and transportation (thematic priority 6) in a framework of EU. It leads to the research financing in a framework of large integral projects. The major European energy equipment and vehicles manufacturers were involved in this as well (Toke, 2006).

An emission problem is so important and wide, the mostly concerned to the ideal combusting of fuels. There are certain ways to decrease these emissions. Such as; continuous dosing of fuel, maintaining high level of temperature in a combustion chamber or choice of optimal fuel humidity (Malaťák et al., 2007).

Stoichiometry analysis of combustion processes is contemplating the characteristics of fuels. They are very important for solving problems raised during designing stage, as well as within a work control of current combustion arrangement. The first step for any stoichiometry calculations of fuels and a thermal work of combustion equipments is an elemental analysis of fuel. Elemental analysis is very important for all of stoichiometry analysis, thermal effectiveness and losses in combustion equipments. It also influences the thermal work of combustion equipment. So called elementary analysis is used during the detection of solid fuels`. This elemental analysis is to find out weight percentage of C, H, O, S, N and water consisted in the fuel (Obernberger et al., 2006; Malaťák et al., 2007).

C, H and O are the main components of solid biofuels and are of special relevance for the gross calorific value, H in addition also for the net calorific value. The fuel N content is responsible for NO, formation. NO emissions belong to the main environmental impact factors of solid biofuel combustion. Cl and S are responsible for deposit formation and corrosion and are therefore relevant for high plant availability. Furthermore, Cl causes HCl. The ash content influences the choice of the appropriate combustion technology and influences deposit formation, fly ash emissions and the logistics concerning ash storage and ash utilization/disposal (Obernberger et al., 2006).

SRF are often topic of discussion. Czech equal term TAP (Tuhá Alternativní Paliva) or German FS (Feste Sekundärbrennstoffe) is covered by Czech norm ČSN CEN/TR 14980. It takes into account contemporary legal regulation of wastes utilization such as fuels. It is covered by several law, touched law are especially law about wastes, covers and atmosphere. SRF are fuels produced directly or indirectly from the biomass. It means these fuels might have biomass basis. SRF are also considered as solid fuels (ČSN ISO 1213-2, 1994).

SRF are disposed from the safety waste which is used for energy recuperation. As well as from the waste is obtained by burning or communally burning of materials regulated by Community environmental legislation (Osowski et al., 2006).

In concordance with terminology, SRF are solid fuels purposely prepared from the safety wastes for its energetic use in incinerator or incineration plant. An alternative fuel might be burnt in the equipment of large or average source of pollution, where the burning tests were done as well as emission parameters tests. The conditions of its use are put on in the list of technical-operational parameters and technical- organization disposal of the source. Such equipments of pollution source are concerned by common emission limits according to a special legislation rule (Malaťák et al., 2005; Rhen et al., 2006).

2. MATERIALS AND METHODS

Component analysis, stoichiometric analyses and emission parameters checking of selected wastes is carried out on compressed material. These might be compressed into different shapes by using various pressures.

There are also used compressed materials into briquettes. If the biofuels are not compressed, they take too much space, volume and transportation, manipulation and storage costs are raised. During firing reach the fast ignition and transmitting of small amount of specific heat. On the other hand parameters of compressed fuels are much profitable and these last longer in hearth during combusting in comparison with uncompressed fuels. A particle analysis of selected solid recovered fuels was done (Table 1). Material mixtures were prepared according to weight unit.

An elemental analysis was done for SRF in order to set basic parameters of fuels. Mostly focused for: water content (weight %), ash matter (weight %), volatile and nonvolatile combustibles (weight %), combustion heat (MJ.kg^{-1}), heating power (MJ.kg^{-1}), $CO_{2\ max}$. (weight %), carbon (weight %), hydrogen H (weight %), nitrogen N (weight %), sulphur S (weight %) and oxygen O (weight %). Fixed elemental analysis was set by elemental analyzer and Perkin Elmer chromatograph device and IKA calorimeter. Final values are given in Table 2. An elemental analysis is necessary part of measurements to set basic stoichiometric and heat properties of judged solid alternative-recovered fuels.

Emission's concentrations of smoke gasses and heat-technical effectiveness are determinate by a gauge GA-60. It is a multifunctional smoke gases analytical gauge. Technical parameters of GA – 60 are mentioned in Table 4.

Combustion equipment is designed to burn any kind of wood or wooden briquettes. Its most important part is a steel plate insert with a thickness of 5 to 8 mm. The sides and the top are covered with special bricks, which accumulate heat and then radiate it for a certain time after the end of heating process

Table 1. Selected fuels – solid recovered fuels

Sample
• Fermented mixture 33 % (rotten fermented waste treatment slurry) and 67 % wood ships, briquettes, 65mm diameter
• Fermented mixture 13 % and 30% wood ships and 47% energy sorrel and coal 10% - briquettes, briquettes, 65mm diameter
• Fermented mixture 16 % and 34 % wood ships and 50% energy sorrel - briquettes, briquettes, 65mm diameter
• Cereals cleaning residues, briquettes, 65mm diameter
• Cereals cleaning residues and meadow grass in a ratio 1:1, briquettes, 65mm diameter
• Cereals cleaning residues and energy sorrel in a ratio 1:1, briquettes, 65mm diameter

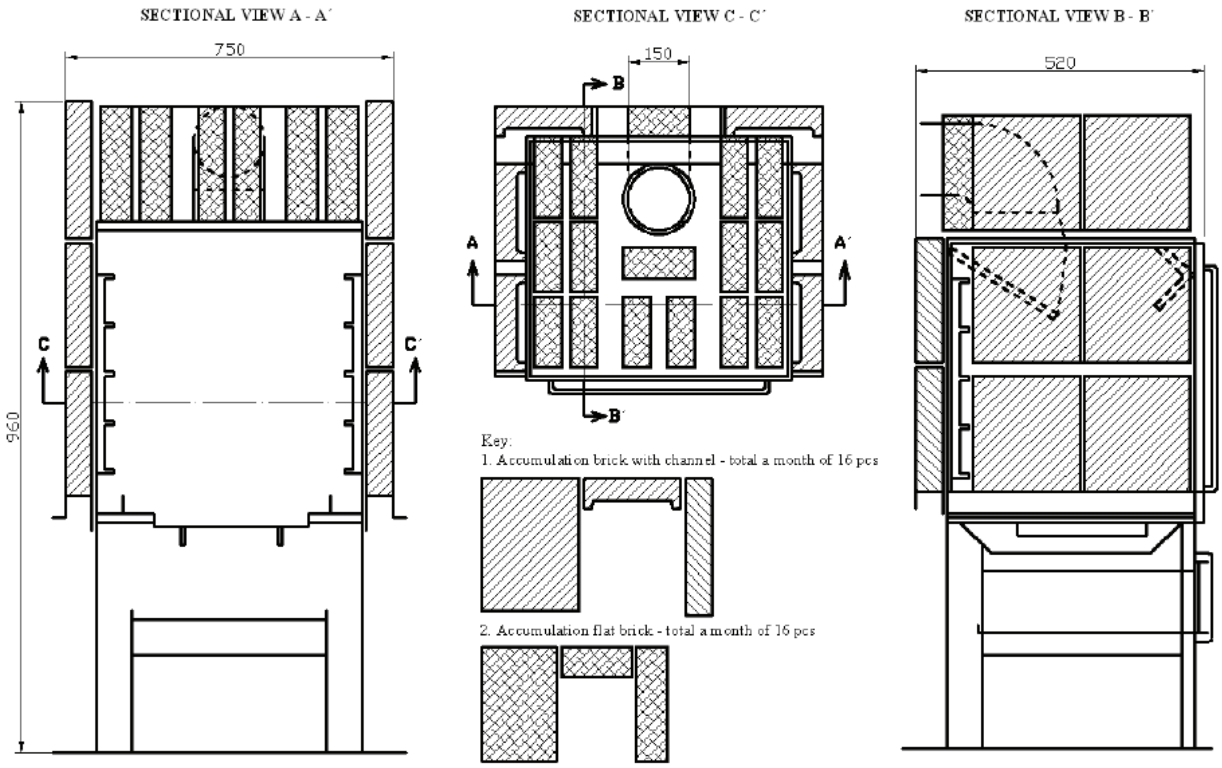

Figure 1. Optimized layout of accumulation bricks of verified combustion stove SK-2 RETAP

Accumulation bricks are covered with an insulation layer of calcium silicate. The door is equipped with ceramic glass with heating resistance up to 750 °C. Emissions are conducted through the flue way of a 150 mm diameter. The accumulation bricks layout in the verified combustion stove SK-2 is shown in Figure 1.

Operation tests were done in accordance with the ČSN EN 13229 standard „Built in heating appliances and open fireplace inserts for solid fuels – requirements and testing methods". For tested heating, a closeable furnace was used. Values of convection passage (these were dependent on rated power) were in a restricted limit range of 12 ± 2 Pa (values of static pressure in a measured area of emissions). The average concentration of carbon monoxide during measurements and other gaseous emissions was counted to a value of 13 % (O_2). By the above-mentioned standard, all average values of carbon monoxide have to meet the limit values for certain class of CO, the same as mentioned in Table 5.

Water and ash matter are consisting into non flammable part of fuel, described as ballast or deadwood. Both of them are decreasing fuel heating power. Their presence straight influences the combustion equipment construction and they are often sources of problems during operations.

All of the main tree fuel components (water, ash water and flammables) are very important factors during combustion process. Their properties influence the construction of combustion equipment as well as its operation regime.

3. RESULTS AND DISCUSSION

An important task of the research project is to set SRF stoichiometry. Stoichiometric calculations of combustion processes are supplementing fuel's characteristics and are also foundation for any heat calculation. These are very important for heat system design problems solving as well as during the heat equipment control.

All of the stoichiometric calculations are recalculated by the weight of total water amount contained in selected samples. Values are also recalculated by the air surplus coefficient for normal conditions (by the temperature t= 0°C and a pressure p= 101.325 kPa) as well as for the referential oxygen amount of combustibles Qr = 13 %. Final parameters stoichiometry calculations of liquid fuels are described in Table 3.

Measurements were focused on emission concentrations produced by combusting the solid alternative-recovered fuels. Carbon oxides (carbon dioxide CO_2 and carbon monoxide CO), nitrogenous oxides (nitrogen monoxide NO and nitrogen dioxide NO_2), sulphur oxides (SO_2) and hydrogen chloride (HCl) were checked. Carbon dioxide was determined by the measured concentration of oxygen and fuel characteristics. According to these measurements, the fuels as well as the combustion equipment are judged in terms of their thermal parameters and emission conditions. Emission's concentrations are set for normal condition of and certain reference amount of

Table 2. Elementary analysis of solid recovered fuels

Sample	Symbol	Fermented mixture 33 % and 67 % wood ships	Fermented mixture 13 % and 30% wood ships and 47% energy sorrel and coal 10%	Fermented mixture 16 % and 34 % wood ships and 50% energy sorrel
Water content (% vol.)	W^r_t	8.04	7.38	9.53
Ash matter (% vol.)	A^r	12.12	12.52	10.31
Volatile combustible (% vol.)	V^r	63.29	56.96	64.78
Nonvolatile combustible (% vol.)	$(NV)^r$	16.55	23.14	15.38
Combustion heat (MJ.kg^{-1})	Q^d_s	16.91	18.06	16.23
Heat power (MJ.kg^{-1})	Q^r_i	15.64	16.76	14.62
Carbon C (% vol.)	C^r_t	42.47	42.89	41.52
Hydrogen H (% vol.)	H^r_t	4.9	5.1	6.3
Nitrogen N (% vol.)	N^r_t	1.18	1.18	1.32
Sulphur S (% vol.)	S^r_t	0.28	0.35	0.19
Oxygen O (% vol.)	O^r_t	31.01	30.48	30.73
Chlorine Cl (% vol.)	Cl^r_t	0.1	0.1	0.1
Sample	Symbol	Cereals cleaning residues	Cereals cleaning residues and meadow grass, 1:1	Cereals cleaning residues and energy sorrel, 1:1
Water content (% vol.)	W^r_t	8.33	8.49	10.69
Ash matter (% vol.)	A^r	6.49	9.5	5.59
Volatile combustible (% vol.)	V^r	71.16	66.63	64.53
Nonvolatile combustible (% vol.)	$(NV)^r$	14.02	15.38	19.19
Combustion heat (MJ.kg^{-1})	Q^d_s	17.86	16.54	16.09
Heat power (MJ.kg^{-1})	Q^r_i	16.25	15.04	14.69
Carbon C (% vol.)	C^r_t	42.62	41.02	42.57
Hydrogen H (% vol.)	H^r_t	6.48	5.95	6.44
Nitrogen N (% vol.)	N^r_t	3.67	1.44	1.36
Sulphur S (% vol.)	S^r_t	0.16	0.13	0.21
Oxygen O (% vol.)	O^r_t	32.05	33.37	33.01
Chlorine Cl (% vol.)	Cl^r_t	0.2	0.1	0.1

oxygen in combustion gases (13 %).

The efficient use of thermal energy by operating the heating appliance in accordance with the data provided by manufacturer and by combusting the experimental fuels is evaluated by rated useful heat efficiency. The measured efficiency has to meet limit values for certain class as presented in Table 6.

Investigation of CO_2 emissions is important due to the fact that they regard the greenhouse gas in question and represent very significant parameter of the conversion process perfection. Its value should range between 8.0...12.5 % (Jevič, 2007). As evident from Table 7, CO_2 value below the above mentioned limit value was for cleaning cereals residues and cleaning cereals residues and meadow grass in a ratio 1:1. These fuels have displayed also the lowest value of heat efficiency (Class 3).

Hydrocarbons and other incompletely burned products have the same characteristics as carbon monoxide. These substances are an important indicator of the burning process quality. A comparison of measured and worked values of CO with CO emission classes showed that all of the briquettes meet the criteria of class 2nd, where the limit is 8000 mg.m^{-3} by 13 % of reference oxygen (Table 5).

NO_x values are easy to measure in the case of all fuels under investigation. There is no limit value for NO_x because of its low heating power. However, if the limit value of NO_x (250 mg.m^{-3} by 11 % O_2) set by the regulation no.3-2002 of the Czech Ministry of the Environment (MŽP ČR) is compared with requirements for granting a certificate „Ecologically safe product“, concerning water heating boilers for central heating systems with the combustion of biomass up to 0.2 MW (ČSN 07 0240 and ČSN EN 303-5 standards), none of fuels tested was found to exceed the limit value.

The excess air coefficient is a very important working parameter influencing both emissions and heating system efficiency. It also determines the amounts of oxidizing parts and a furnace temperature. It is possible to determine optimal working temperature in the case of heating appliances of this class in a power range ($2.53 \leq n \leq 5.8$). The values

Table 3. Final stoichiometry calculations of solid recovered fuels

	Sample	Fermented mixture 33 % and 67 % wood ships	Fermented mixture 13 % and 30% wood ships and 47% energy sorrel and coal 10%	Fermented mixture 16 % and 34 % wood ships and 50% energy sorrel
O_{min}	Theoretical quantity of oxygen for ideal combustion process ($m^3.kg^{-1}$)	0.849	0.872	0.91
L_{min}	Theoretical air quantity for ideal combustion process ($m^3.kg^{-1}$)	4.042	4.152	4.334
n	Overflow of the air (O_2 = 13 %)	2.65	2.65	2.65
v^s_{spmin}	Theoretical cubical quantity of dry combustion gas ($m^3.kg^{-1}$)	3.954	4.048	4.165
CO_{2max}	Theoretic cubical concentration of oxide carbonic in dry combustion gas (%vol.)	19.92	19.65	18.49
	Sample	**Cereals cleaning residues**	**Cereals cleaning residues and grass, 1:1**	**Cereals cleaning residues and energy sorrel, 1:1**
O_{min}	Theoretical quantity of oxygen for ideal combustion process ($m^3.kg^{-1}$)	0.931	0.863	0.922
L_{min}	Theoretical air quantity for ideal combustion process ($m^3.kg^{-1}$)	4.435	4.107	4.389
n	Overflow of the air (O_2 = 13 %)	2.65	2.65	2.65
v^s_{spmin}	Theoretical cubical quantity of dry combustion gas ($m^3.kg^{-1}$)	4.282	3.979	4.227
CO_{2max}	Theoretic cubical concentration of oxide carbonic in dry combustion gas (%vol.)	18.46	19.12	18.67

determined by this interval were obtained by burning briquettes - in first two from three of working measurements fermented mixture 33 % and 67 % wood ships (n= 2.53).

The highest efficiency at nominal heat performance, i.e. higher or equal to 70 % (Class 1) have been reached by the briquettes produced from mixture of fermented mixture 33 % (rotten fermented waste treatment slurry) and 67 % wood ships and mixture of fermented mixture 13 % and 30% wood ships and 47% energy sorrel and coal 10%. The briquettes from mixture of fermented mixture 16 % and 34 % wood ships and 50 % energy sorrel and mixtures of cereals cleaning residues and energy sorrel in a ratio 1:1 can be classified into the class 2. As that of low technical - thermal effect combustion class 3 can be specify by the briquettes from cleaning cereals residues and mixture of cleaning cereals residues and meadow grass in a ratio 1:1 (Table 7).

Table 4. Technical parameters of GA-60 analyzer

	Range	Resolution	Indicator accuracy
Surrounding temperature/indicator Pt 500	0 – 100 °C	1 °C	± 2%
Combustion gases temperature	0 – 1 300 °C	1 °C	± 5%
Indicator NiCr/Ni (or PtRh/Pt)	0 – 1 600 °C	1 °C	± 2%
Electrochemical converter/Oxygen (O_2)	0 – 20.95%	0.01%	± 2%
Electrochemical converter /Carbon monoxide (CO)	0 – 20 000 ppm	1 ppm	± 5%
Electrochemical converter /Nitroso compounds (NO)	0 – 5 000 ppm	1 ppm	± 5%
Electrochemical converter /Nitrogen dioxide (NO_2)	0 – 800 ppm	1 ppm	± 5%
Electrochemical converter /Sulphur dioxide (SO_2)	0 – 2 000 ppm	1 ppm	± 5%
Pressure	± 50 hPa	0.01 hPa	
Soot number by Bacharach	0 - 9	1	
Nitrogen compounds (NO_x) as NO_2/calculation from NO+NO_2	0 – 6 000 ppm	1 ppm	
Carbon dioxide (CO2)/calculation by fuel from CO2max and O2	0 – 25%	0.1%	
Thermal – technical efficiency/calculation by DIN	0 – 100%	0.1%	
Stack loss and loss by imperfect combustion/ calculation by DIN	0 – 100%	0.1%	
Air surplus/ calculation by DIN	1 - ∞	0.01	

Table 5. Classes of carbon monoxide emissions for local heating appliances designed for solid fuel combustion (ČSN EN 13229)

Appliance CO emission class	Heating appliances with close doors
	Limit values of CO emission classes (at 13 % O_2) (%)
Class 1	≤ 0.3*
Class 2	> 0.3 ≤ 0.8*
Class 3	> 0.8 ≤ 1.0*

* 1 $mg.m^{-3}$ = 0.0001 %

Table 6. Efficiency classes for local heating appliances designed for solid fuel combustion (ČSN EN 13229) by rated useful heat

Efficiency class of heating appliances	Heating appliances with close doors
	Limit values of class efficiency (%)
Class 1	≥ 70
Class 2	≥ 60 < 70
Class 3	≥ 50 < 60
Class 4	≥ 30 < 50

Further were measured NO_x and HCl emissions. NO_x values were significantly lower than limit values determined for similar combustion of solid biofuel. Higher differences of HCl emissions correlate with various Cl content in fuels. Fuels have shown considerably lower values.

4. CONCLUSION

The low CO emissions, when the limit value of 8000 $mg.m^{-3}$ at 13 % of O_2 has not been exceeded, have been reached by the all briquettes. The highest efficiency at nominal heat performance, i.e. higher or equal to 70 % have been reached by the briquettes produced from mixture of fermented mixture 33 % (rotten fermented waste treatment slurry) and 67 % wood ships, fermented mixture 13 % and 30 % wood ships and 47 % energy sorrel and coal 10 %. Further were measured NOx and HCl emissions. NOx values were significantly lower than limit values determined for similar combustion of solid biofuel. Higher differences of HCl emissions correlate with various Cl content in fuels. Fuels have shown considerably lower values.

The results have proved better heat-technical and emission parameters of blended briquettes and are significant also for solid biofuels and SRF standardization as well as for increasing efficiency method detection and ecological parameters optimization including HCl emissions.

Selected SRF from agricultural wastes show good emission parameters given by class 2 and effectiveness in a range of classes 1 to 3. These might be suitable for similar local heating systems after the proving of other certificate requirements.

In a long time perspective of maintainable development is very important to use such energy sources most effectively. It naturally should be optimized financial resources use in order to limit – if it's possible, harmful human health influences and environment. It also works for surplus creating for all parts of world population.

The definite determination of typical physical-chemical properties is necessary for designing, building and checking of combusting equipments and for the thermal use of agricultural wastes. Burning of agricultural wastes is useless without meeting these premises.

In a medium time perspective greenhouse gases emissions produced by human activities are influencing climatic changes. These should be set by acceptable methods. An impact of short time effect to energy supply for example is inconsiderable.

SRF are fuels provided from the safe wastes sources. These are used to recuperate energy from the wastes by burning or common burning regulated by the legislature of common environments.

SRF are becoming to play an important role in EU common energy policy. Costs and benefits analyses have shown that SRF usage contributes to the decrease of greenhouses gases emissions. SRF use might be especially important in under peopled areas. It also works as an instrument to achieve goals required by direction of land- fills by the decreasing of deposited biodegradable wastes amount.

SRF might replace fossil fuels and due to limit wastes volumes deposited in land fills. It leads to the improvement of fuel source effectiveness. Their use is going to limit of fossil carbon emissions to the atmosphere and the amount of greenhouse gases produced by anthropogenic activities, if these are biomass based. SRF based on biomass are able to store solar energy.

Support of the agricultural non food production for its use such as renewable energy source is considered as a perspective way not only in the meaning of ecology aspect.

Table 7. Average parameters of results of working measurements of gaseous and heat-technical parameters

	Combustion gas temp.	O_2	n of O_2	CO_2	CO (O_2=13%) / CO emission class	SO_2 (O_2=13%)	HCl (O_2=13%)	NO_x (O_2=13%)	Technical-thermal combustion efficiency / Class of heating
	°C	%	-	%	$mg.m^{-3}$	$mg.m^{-3}$	$mg.m^{-3}$	$mg.m^{-3}$	%
Fermented mixture 33 % and 67 % wood ships - briquettes, 65mm diameter	474.58	12.23	2.531	8.66	3562.4 / Class 2	0.0	13.59	140.35	85.1 / Class 1
Fermented mixture 13 % and 30% wood ships and 47% energy sorrel and coal 10% - briquettes, 65mm diameter	451.2	13.23	3.23	9.05	4644.5 / Class 2	2.56	42.06	200.31	81.3 / Class 1
Fermented mixture 16 % and 34 % wood ships and 50% energy sorrel - briquettes, 65mm diameter	368.24	11.85	3.00	8.31	6763.0 / Class 2	1.03	56.04	118.63	62.7 / Class 2
Cereals cleaning residues - briquettes, 65mm diameter	288.15	16.16	5.08	7.85	7350.53 / Class 2	0.0	81.01	223.78	51.5 / Class 3
Cereals cleaning residues and meadow grass in a ratio 1:1, briquettes, 65mm diameter	269.54	18.5	5.8	7.29	7890.32 / Class 2	0.0	65.21	156.56	46.5 / Class 3
Cereals cleaning residues and energy sorrel in a ratio 1:1, briquettes, 65mm diameter	365.52	11.56	3.14	8.12	6582.0 / Class 2	1.05	25.04	198.12	61.1 / Class 2

Bio-fuels are not competitive with the classical energy sources without this support. Current agrarian policy of EU accentuates for such use of agricultural production as most significant alternative toward the EU agricultural production restriction. A state support is necessary for SRF to gain a larger share on market.

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