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Research Article

Improvement of Thermal Processes for Using Residues from Bioethanol and Sugar Production in Brazil: Experiments and Proposed Optimization Measures

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Within a national funded Brazilian-German cooperation project ASHES, the thermal utilization of bagasse and other residuals from the sugar processing industry was examined. The characterization of the ashes was also performed but it is not in the focus of this paper. To determine the relevant combustion parameters, tests were carried out in a laboratory-scale, fixed bed reactor (KLEAA) at KIT-ITC. Subsequently, Fraunhofer UMSICHT carried out tests in continuously operated combustion plants with different plant sizes of 30 kW, 100 kW, and 440 kW. All relevant compositions were analyzed by CUTEC. The primary objective was to gain knowledge regarding the combustion and emission behavior of the fuels. These findings were used to identify optimization potentials at various points and elaborate concepts for their improvement. In the next steps of the project, optimization of these concepts will be the focus. In cooperation with the Brazilian project partners, several of them should be implemented into practice after the project.

1. Background

Brazil holds a 25 % share in the global sugar production, which makes it the world's largest sugar producer; its 50 % share in exports makes it the world's largest exporter. A share of approximate 20 % of the world production makes the country number two among the largest ethanol producers next to the USA. In Brazil, 16 % of the energy demand is satisfied by ethanol and electricity generated from sugarcane, which makes this plant the most important renewable energy resource of the country [1, 2].

In the 2013/2014 season, Brazil processed 653.5 million Mg of sugarcane into 37.7 million Mg of sugar and 27.5 million m^3 of ethanol in nearly 400 sugar factories [3, 4]. Sugarcane processing leaves as a residue bagasse with a water content of approx. 50 % and filter cake. Part of the straw is left on the field. In Brazil, almost 180 million Mg (w = 50 %) of bagasse are used for incineration in simple furnaces with a low energy yield. Frequently, these furnaces represent no longer the state of the art [4, 5].

While in the past the main concern was the disposal of bagasse, together with providing energy for the production plants, the production of electricity gained importance. Now, it has become a relevant market for the plant operators. Against this background, improved efficiency, the use of sugarcane straw to increase the potential for electricity generation, and reduction of emissions in the course of plant modernization are urgent topics [6]. Within the framework of a bilateral cooperation project funded by the German BMBF, the combustion behavior and gasification of sugar and ethanol production residues were studied in laboratory and technical-scale plants. A variety of optimization measures for practical application were designed and assessed.

2. Procedure and Methodology

At the beginning, besides a standard analysis, the feedstock was subjected to comprehensive practical tests. These tests served to obtain detailed information about the combustion

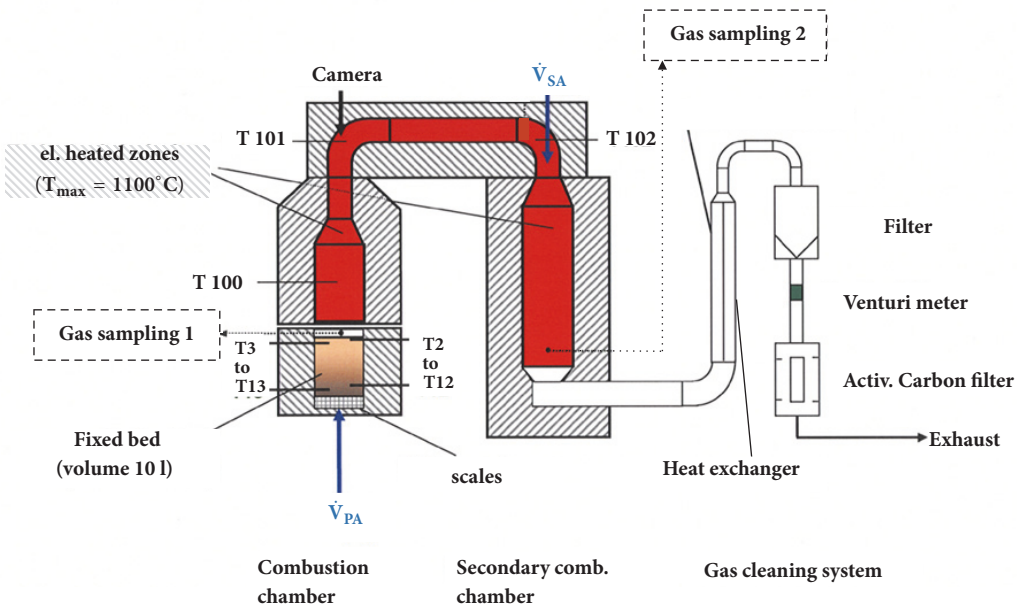


Figure 1: Schematic view of the fixed bed reactor KLEAA [9, 11].

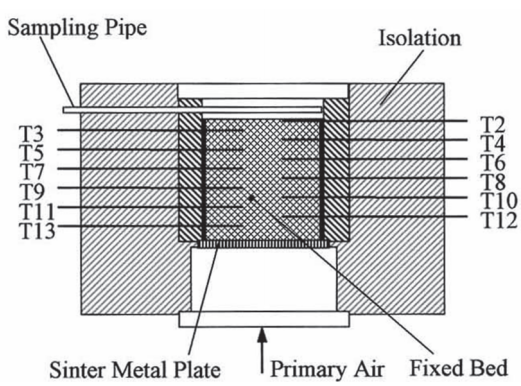


Figure 2: Schematic image of the combustion vessel.

characteristics of the feedstock and generated target quantities for advanced development of the plants especially with regard to efficiency and emissions. The first task was performed in a lab scale fixed bed reactor, while data regarding emission issues were measured in a continuously operated grate incinerator.

In the laboratory facility of KIT-ITC (acronym "KLEAA"), the fuels were characterized in respect of ignition rate, mass conversion rate, and reaction front velocity. The major components of the facility are represented schematically in Figure 1. A more detailed description of the facility is available elsewhere [7–10].

The arrangement of the thermocouples inside the furnace is shown in detail on Figure 2. Six thermocouples at a distance of 20 mm are ordered at each side of the reactor. The thermocouple shift between the opposite sides is 10 mm.

Figure 3 shows the fuel bed temperatures as a function of time. In the ignition phase, the fuel bed surface dries and ignites by radiation heat transfer from the furnace. Within 1.8 min the temperature increases rapidly to about 800°C, as measured by thermocouple T2 (blue). This time is defined as the ignition time [9, 11]. The main factors influencing the ignition time are the water and volatile content, as well as the particle size of the fuel. The reaction front propagates with an almost constant velocity in a direction opposite to the primary air flow. The position of the reaction front is derived from the inflection point of the temporal temperature curves. The straight line on Figure 3 represents the reaction front position, described by the temperature change measured by thermocouple T2 through T13. The slope of the line indicates the reaction front velocity (see 1). The ignition rate describes the amount of fuel which ignites for a certain time on a certain area. According to (2), its value (0.062 kg $s^{-1}m^{-2}$) is obtained by multiplying the reaction front velocity with the initial bulk density of the fuel. In the main combustion phase, the overbed temperature is almost constant. At the reaction front, high temperature gradients are generated. Due to the low heat conductivity, the fuel bed remains practically unaffected below the reaction zone. The temperature increase at the end of the combustion process indicates the char burnout close to the vessel bottom (T13, grey). The determination of the characteristic numbers is summarized in Table 1.

In the present example, the reaction front velocity for the investigated wood chips is 18.5 mm min^{-1}. The initial water content of the chips, as cut from a whole tree, was about 50 wt.-%. After one month air drying in the storage the water content dropped to about 15 wt.-% [12, 13].

Figure 4 shows the mass decrease as a function of time. During the ignition phase (defined by the ignition time), the mass decrease is only due to the evaporation of some water

Table 1: Overview of the characteristic numbers [11].

Equation 1	reaction front velocity	$u_{RFV} = \frac{dx}{dt} \left[\frac{m}{s}\right]$
Equation 2	ignition rate	$IR = u_{RFV} * \rho_{bulk} \left[\frac{kg}{s * m^2}\right]$
Equation 3	mass conversion rate	$MCR = \frac{\dot{m}_{fuel}}{A \cdot (1 - \xi_{ash})} \left[\frac{kg}{s * m^2}\right]$
Equation 4	specific heat release rate	$HR = MCR \cdot LHV \left[\frac{MW}{m^2}\right]$

x = height of the reactor [m]; ρ_{bulk} = bulk density of the initial fuel [kg m^{-3}]; m_{fuel} = fuel mass converted [kg]; A= cross-section of the combustion vessel [m^2]; ξ_{ash} = ash content of the fuel [-]; and LHV = lower heating value [MJ/kg].

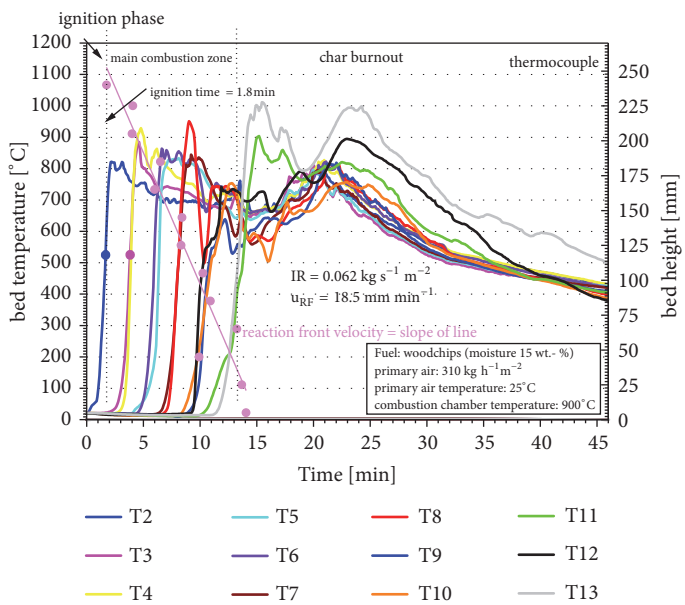


Figure 3: Temperature distribution and the position of the reaction front in the fuel bed [11].

and to some pyrolysis species; hence, it is almost negligible (see Figure 4). In the course of the main combustion phase, the mass decreases linearly. This decrease is defined as the mass conversion rate I (MCR I). Its value of 0.047 kg s^{-1} m^{-2} is obtained according to (3). The MCR I ends, when the ignition front reaches the grate bar. The remaining burnout is described by the MCR II, which could be approximated by a linear function from the remaining mass of the main combustion zone (MCR I) to the final amount of ash. Multiplication of the mass conversion rate (MCR) by the lower heating value (LHV) gives the specific heat release rate (HR) (see 4). This number is an important indicator if a grate boiler operates in its family of characteristics of a power chart. In grate firings, the specific heat release rate should be below 1 MW m^{-2} [9, 11].

In Table 1, the main characteristic numbers are summarized.

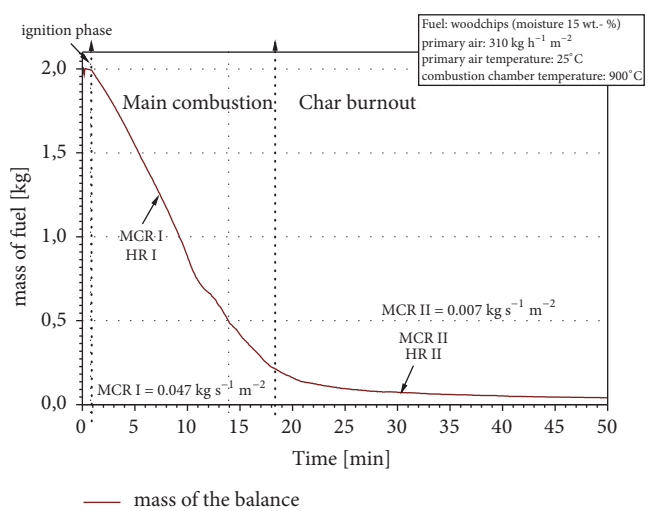


Figure 4: Mass decrease in the fuel bed [11].

3. Results

Figure 5 shows selected results of the analysis of the investigated fuels. The analysis of the fuels and the ashes was carried out by CUTEC.

The wood chips used in these experiments are a mixture of pinewood and hardwood. The chemical composition of the chips is in a good agreement with previous results ([11, 14, 15],

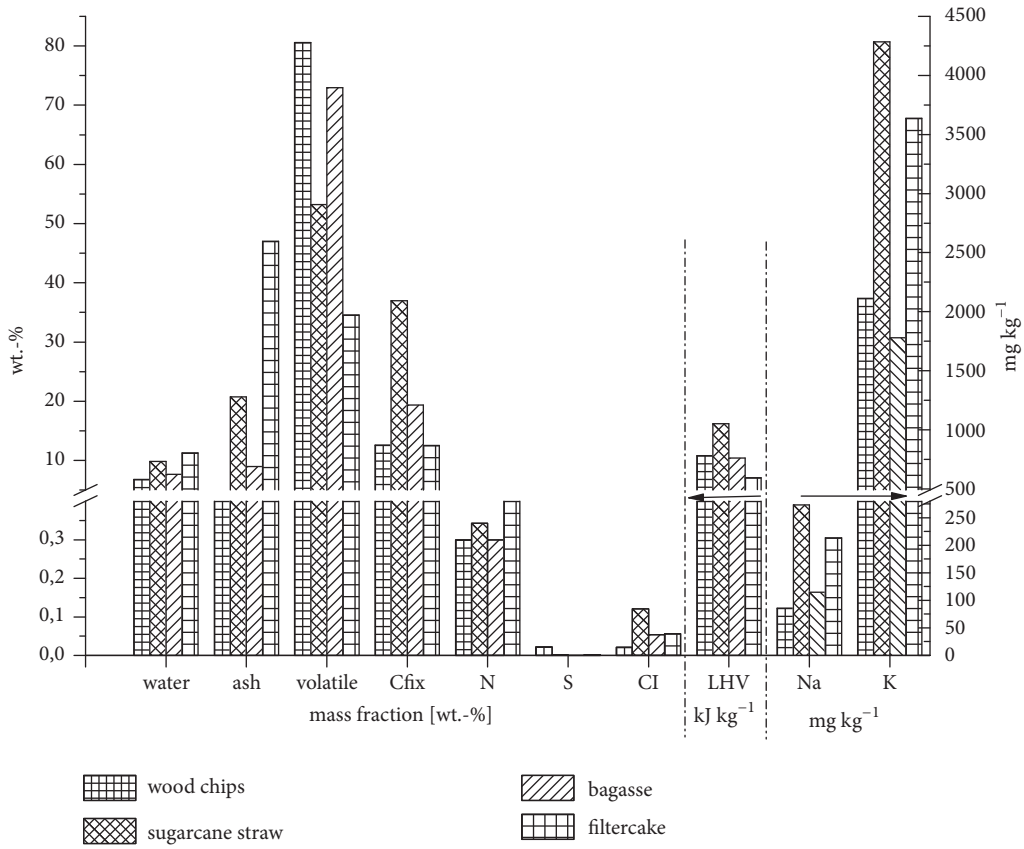


Figure 5: Comparison of selected fuel parameters.

p.6). In order to characterize the combustion behavior of the sugarcane residues (straw, bagasse, and filtercake), their combustion is compared with that of the wood chips as a reference.

The fuels sugarcane, bagasse, and filtercake were collected onsite in Brazil. Prior to the transport they dried and compressed. It is an original fuel. The (chemical) content of natural materials varies within a given range. Because of different soils, weather conditions, etc., the composition varies naturally. Wood is also susceptible to them. The content given here is at the mid-range.

The difference in the water content of the fuels is low (between 7 and 11 wt.-%). Consequently, this parameter has no significant influence on the combustion behavior. The filtercake has the highest ash content and the lowest volatile fraction. The chlorine content of the sugarcane straw is twice as high as that one of bagasse and filtercake. The chlorine content of the wood with 0.02 wt.-% is still under the limit of 0.03 wt.-% (water free) for wood (pellets) class B [15, p. 6]. The chlorine content of sugarcane straw of 0.12 wt.-% is comparable to that of waste wood [16, p. 15, table 1]. Thus, the chlorine content of the residues is of a concern for the emissions (Table 5). Since concentrations are comparable with these of old woods, we do not expect problems concerning slag formation and corrosion.

Figure 6 shows the particle size distributions of the fuels. Both the mean particle sizes and the width of the size distribution differ slightly, between 5 and 11 mm. The particle size distribution influences the specific surface and therefore the mass and heat transfer. Since the investigated fuels were packed in a bagged cargo, compression and agglomeration inside the bag during shipping took place.

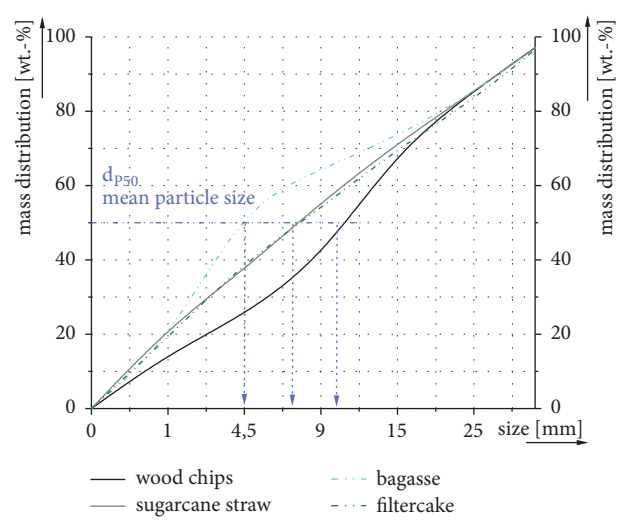


Figure 6: Measured particle size distributions.

Table 2: Overview of equations for the mean particle size.

Equation 5	surface partial	$A_p = \pi * d_{p,50}{}^2 \ [mm^2]$
Equation 6	volume partial	$V = \frac{\pi * d_{p,50}{}^3}{6} \ [mm^3]$
Equation 7	specific surface area	$S_v = \frac{A_p}{V} \left[\frac{1}{\text{mm}}\right]$

where A_P = area of the particles [mm^2]; $d_{P,50}$ = mean particle size [mm]; V = volume [mm^3]; and S_V= specific surface area [mm^{-1}].

Table 3: Physical properties of the fuels.

	$d_{p,50}$ [mm]	A_p [mm^2]	V [mm^3]	S_v [mm^{-1}]	ρ_{bulk} [kg m^{-3}]
wood chips	11	380	697	0,545	170
sugarcane straw	8	201	268	0,750	50
bagasse	5	64	48	1,333	64
filtercake	8	201	268	0,750	290

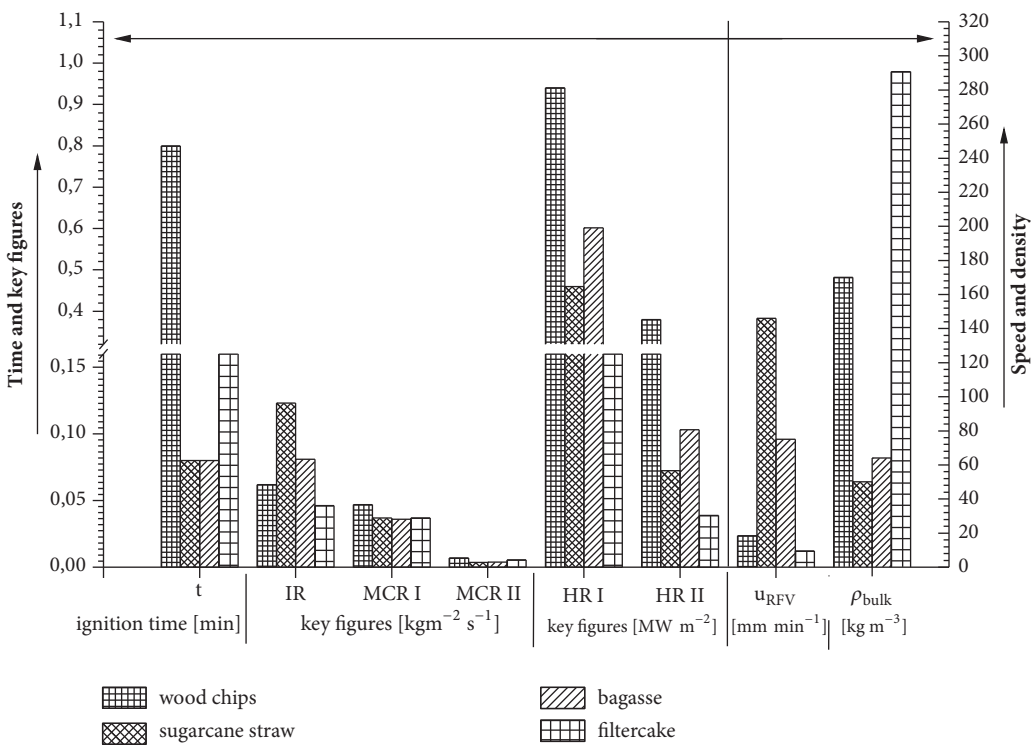


Figure 7: Comparison of characteristic figures as determined from preliminary experiments.

The wood chips have mean particle size around 11 mm, which is in a good agreement with previous results [14]. The size of the sugarcane straw particles (mean size ≈ 8 mm) is comparable to that one of the filtercake (mean size ≈ 8 mm). In contrast, the bagasse particles are about 37 % smaller (mean size ≈ 5 mm). The formulas used to calculate relevant sizes in terms of particle size and specific surface area are summarized in Table 2.

Table 3 shows calculated particle size and specific surface area.

Assuming spherical particles the specific surface varies according to the mean particle size. The bulk density differs significantly, too: while sugarcane straw and bagasse have nearly the same bulk density, filtercake has the highest one. For bagasse it is more than twice compared to wood chips, but it is in a comparable size within sugarcane straw and filtercake.

3.1. Experiments in a Laboratory-Scale Plant. The parameters describing it were calculated according to equations (1)-(4), while the experiment data were obtained in a series of trials carried out in a laboratory-scale plant at KIT-ITC (Figure 1). Figure 7 shows the key characteristics of the combustion for wood chips, bagasse, sugarcane straw, and filter cake.

Table 4: Factors influencing the combustion and results of the tests.

	water	volatile	ρ_{bulk}	dp	Lignin	u_{RFV}
	wt-.%		kg m^{-3}	mm	wt-.%	mm min^{-1}
wood chips	7	81	170	11	26	19
sugarcane straw	10	53	50	8	7	146
bagasse	8	73	64	5	10	75
filtercake	11	35	290	8	7	10

Table 5: Averaged emission levels at 11 % O_2 from a grate furnace of 440 kW. Duration of the experiment: approx. 40 h.

	HCl	CO	SO_2	NH_3	NO_x	Dust
	mg/m$^3{}_N$	mg/m$^3{}_N$	mg/m$^3{}_N$	mg/m$^3{}_N$	mg/m$^3{}_N$	mg/m$^3{}_N$
bagasse pellets	38.65	<10	169.93	10.21	96.99	52.5
sugarcane straw	115.20	<10	172.88	8.41	24.40	136.49

The ignition time of the investigated fuels is between a couple of seconds and one minute. It differs significantly from that one of wet fuels like natural wood chips, which has water content of about 40 wt.-% and ignition time of several minutes [7]. Therefore, the differences in ignition time for the investigated fuels are rather statistical reasonable. In general, the reaction front velocity (u_{RFV}) depends higher on the water and volatile content, the bulk density, and the mean particle size. These parameters are listed in Table 4.

The differences in water content could be neglected, while the differences in bulk density volatile content and lignin are apparent. The mean particle size has to be considered for the comparison of the combustion behavior of bagasse and wood chips. Biomass has three main constituents: cellulose, hemicellulose, and lignin. Since the cross-linking among them is differently strong, their stability also varies. Lignin has the strongest cross-linking of all and so the greatest stability. Thus, most of the energy is used to break its structure. The energy needed to decompose the cell walls increases from sugarcane straw to wood chips, as the fractions of hemicellulose, lignocellulose, and lignin of the fuels increase from sugarcane straw to wood chips. Because of increasing stability of the molecular structure, decomposition of these materials takes more energy. There exist a linear dependency between the reaction front velocity and the volatile content (increase of volatiles induces higher velocities) [9]. In opposite, there is an inverse function of the u_{RFV} with the bulk density [17]. Decreasing bulk density causes energy transfer by means of thermal radiation through the hollows and porosity of the fuel bed. The thermal conduction through the solid to the fuel layer underneath is decreased. This relation is presented clearly in Figure 7 and Table 4: the wood chips and bagasse have similar volatiles content, 81 wt.-% and 73 wt.-%, respectively. The lignin fraction of the wood chips is 26 wt.-%, much higher than that of bagasse, 10 wt.-%. In opposite, the bagasse bulk density, 64 kg m^{-3}, is significantly lower compared to that of the wood chips, 170 kg m^{-3}. The reaction front velocity of a solid fuel increases with decreasing bulk density, decreasing particle diameter (which correlates with increasing specific surface), and decreasing stability of the molecular structure. The straw has the lowest bulk density and the highest u_{RFV}, compared, e.g., to the filtercake with the highest bulk density and the lowest u_{RFV}, while the decrease of the volatile content of a factor of 1.5 (from 53 wt.-% to 35 wt.-%) supports the decrease of the u_{RFV} from sugarcane straw to the filtercake. The lower mass conversion rates (MCR I and II) of sugarcane straw and bagasse compared to wood chips indicate that, for "classical" grate furnace operations, the lower mass conversion would result in the need of an increase of the necessary grate length. All investigations were performed in a fixed bed without stoking. In continuously operated grate incinerators, this is an important parameter to influence the combustion behavior.

Based on these findings about the combustion characteristics, the substitution of wood chips with bagasse, filtercake, and sugarcane straw or mixture of these fuels is an option for existing grate incinerators. The heating rate (HR) on the grate is much lower for bagasse and sugarcane straw than for wood chips (Figure 7). Consequently, there is no need to fear excessive thermal load on the grate in a conventional plant, when wood chips are partially replaced by bagasse, straw, or filtercake. The results of laboratory studies show that the fuels can be substituted for each other within this range of boundary conditions and chemical composition. A substitution is not to be counted with increased corrosion or slag formation. Horseshoe furnace is Brazil's best available technology by now. However, from our perspective, based on the results burning of the residues materials in a classical grate is possible. At present, bagasse is predominantly thermally utilized, though direct removal of the filtercake is problematic (acidification of the soil). Additionally, the energy utilization factor has to be increased. Therefore, the residues need to be increasingly used for energy recovery. This is the reason why filtercake and straw were tested as material.

While the experiments in the fixed bed reactor give basic answers to the question of the combustion characteristics of the solid biofuels described with key numbers necessary information about emission characteristics and assessment of transport issues were in the foreground of the Fraunhofer UMSICHT with various fuel mixes in technical scale. The

tests were run in different furnaces in a performance range between 30 kW and 440 kW. The CUTEC institute was responsible for the analysis of the samples. Because of the technical issues, bagasse pellets were used for the thermal investigations at Fraunhofer UMSICHT. The pellets were also produced in Brazil. Their content is similar to that of the bagasse from the combustion study at KLEAA. For longer transportation pelletizing is meaning full. At a single USINA only about 40 % of the accumulated bagasse is locally burned. Pelletizing allows the bagasse application as a fuel for households or other plant operators.

Based on the experimental results and those of plant inspections in Brazil, various approaches for solutions were designed for implementation along various time horizons, a selection of which is described in optimization measures.

At the plants we have visited only bagasse is burned at present. According to our interviews with the operators, cofiring has to be implemented in the future. All inspected plants have "horseshoe furnace". The aim of the project was to study different (scenarios for) fuels mixtures. In this paper only a small fraction of the results is published. They refer mostly to the energy utilization and improvement of the local fertilizer situation. Energetical utilization of the residual materials resulted in application of the ash as a fertilizer. The excessive use of "unprocessed" bagasse, vinasse, etc. as a fertilizer has a negative environmental impact due to soil acidification. In opposite, the application of the ash obtained by the energetical utilization of the sugar production residues as a fertilizer results neither in soil acidification or water pollution. Here one confronts with soil acidification and other environmental issues, CO_2 concentration, over fertilization, NO_x, fine dust, etc. Furthermore, energetical utilization of the residual carbon in the biomass reduces the greenhouse gases. This is a profit for the climate. By energetical and material utilization higher overall economic efficiency of the process was achieved. Fewer fertilizers will be used, and more energy will be generated.

3.2. Conversion Tests on a Continuously Operated Grate. Experiments in furnace plants on a technical scale using bagasse, sugarcane straw, and various blends of them conducted by Fraunhofer UMSICHT showed that highly efficient combustion with low contents of residual carbon in the ashes and low CO emissions is possible. The quality of bagasse makes transport of bagasse difficult. Compaction however not only improves transportability by a considerable degree, but also makes possible the use of feed screws, which allows operation in smaller decentralized systems. Moreover, dust emissions are reduced still further. The use of straw compared to gas leads mainly to higher dust emissions and increasing chlorine concentrations.

The increase of HCl in the case of straw corresponds directly to the increase of chlorine content in the straw, which is roughly twice as high as in bagasse. Similar explanation can be given for the dust emissions: alkalis are known as precursor for aerosol formation [18–20]. In the straw sodium and potassium have much higher concentration than in the bagasse, so the amount of dust for straw increases. The NO_x- formation strongly depends on temperature, mixing conditions, and residence time distribution in the flue gas. The comparable high NOx concentration for bagasse could not be explained by the N- content in the fuels, while bagasse and straw have nearly the same nitrogen content. The sulphur content in the fuels is nearly the same, and the SO_2-concentrations are plausible.

Table 6: Comparison of scenarios.

	η_{el}	η_{ges}
Case 1: ideal case	16 %	29 %
Case 2: real case	8 %	19 %
Case 3: optimization	15 %	28 %

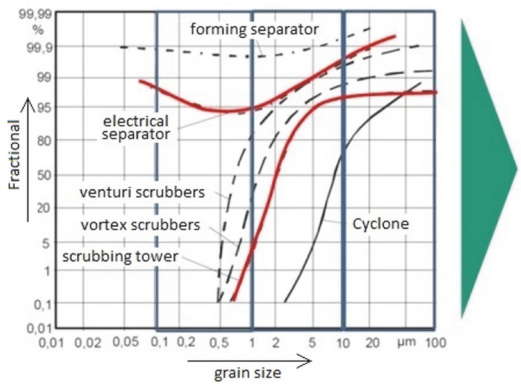
4. Optimization Measures

4.1. Efficiency Considerations. An existing plant was modeled and balanced with respect to optimization measures in the light of the results obtained in the different experimental series and from data collected in a technical inspection.

Three cases were examined. Case 1 describes the ideal one in which combustion of bagasse is considered in a horseshoe furnace with a water content from bagasse of 40 % and an air ratio of 1.5 without any losses. In Case 2 (real case), losses are additionally taken into account. In Case 3, an upstream stage of fuel drying is evaluated. The fuel losses in Cases 2 and 3 were calculated by way of an equilibrium of forces of the bagasse particles added, from a particle size distribution curve, and from the air and off gas streams added. The fuel losses considered were only losses into the ash disposed of, not via, the flue gas. The air ratio was kept constant. The use of waste heat from the process of drying the fuel can be used to clearly increase the electric and thermal efficiency of the plant, thus adding to the optimization of electric and thermal efficiency (Table 6).

4.2. Environmental Aspects. Power plants in Brazil normally are equipped with simple scrubbers, most of them operated with fresh water. On the one hand, these systems are weak with respect to their removal characteristics, especially when it comes to fine particles; on the other hand, their use is associated with a high consumption of water. The emitted particles do not stay at the site. Brazil aims to increase the energy efficiency and to improve the environmental aspects of the facilities. Consequently, the motivation to keep the pollutant and particle emissions as low as possible is high. With this knowledge, a number of considerations were elaborated: results for potential backfitting options are shown below.

As electrostatic separators show low pressure losses, it would be rather simple to backfit them into an existing system. Estimates are represented in Figure 8 and Table 7, showing the reduction effects that could be achieved for fines with regard to the entire system of facilities. In this case, it was assumed that currently all plants are operated with a scrubber and, on the average, precisely comply with applicable limits relative to aggregate dust (TSP).



Fractional

[%]	PM 1	PM 10	>PM 10
fabric filters	99,75	99,775	99,97
electr. separators	96,5	97,25	99,725
venturi scrubbers	40	89,7	99,65
vortex scrubbers	10	59	98,5
scrubbing tower	1	49	96
Cyclone	0	32,5	82

Figure 8: Schematic diagram showing procedure to determine fines reduction potential as a result of optimization of existing plant technology ([21], S. 536(translation from the KIT) [22]).

Table 7: Results of various scenarios.

Scenario	TSP [to/a]	Reduction potential, dust emission [%]
(1) Plants meet applicable limits	131,313	
(2) Maximum modernization	3,582	97.3%
(3) Dimensioning to 50 mg/Nm^3 limit	15,545	88.2%
(4) Dimensioning to 100 mg/Nm^3 limit	31,091	76.3%

5. Summary

Within the framework of the Brazilian-German ASHES cooperation project funded by the German BMBF, it was possible to obtain crucial knowledge about the combustion characteristics of bagasse and other residues from sugarcane processing. The key data for the transfer of the data to a classical grate were determined by comparison of the three common residues in sugarcane plantations with woodchips. The lower mass conversion rates (MCR I and II) of sugarcane straw and bagasse compared to wood chips indicate that, for "classical" grate furnace operations, the low mass conversion would result in the need to increase the necessary grate length or for existing plants an adaption of the operational parameters to increase the mass conversion rate, e.g., by stoking of the fuel. The heating rate (HR) on the grate is much lower for bagasse and sugarcane straw than for wood chips. Consequently, there is no need to fear excessive thermal load on the grate in a conventional plant. The results of laboratory studies show that the fuels can be substituted for each other within this range of boundary conditions and chemical composition. By this substitution, there is no risk of increased corrosion or slag formation. Horseshoe furnace is Brazil's best available technology by now. However, from our perspective, based on the results burning of the residues materials in a classical grate is possible. At present, bagasse is predominantly thermally utilized, though direct removal of the filtercake is problematic (acidification of the soil). Additionally, the energy utilization factor has to be increased. Therefore, the residues need to be increasingly used for energy recovery. This is the reason why filtercake and straw were tested as material.

The theoretically considered optimization shows that, with few optimizations, a significant increase of the efficiency is possible. The excess of waste heat from the process of drying the fuel can be used to increase the electric and thermal efficiency of the plant, thus adding to the optimization of electric and thermal efficiency. By modernizing the dust separation, it is possible to reduce dust emissions by up to 97 %.

These results are currently being used to reveal optimization potentials at various places in Brazil and their implementation in practical cooperation with the partners.

Abbreviations

ASHES: Rückführung von Nährstoffen aus Aschen von thermo-chemischen Prozessen mit Bagasse bzw. Bagassestroh(return of nutrients from ashes of thermochemical processes with bagasse or bagasse straw)

BMBF: Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)

CUTEC: Clausthaler Umwelttechnik Forschungszentrum

ITC: Institut für Technische Chemie(Institute for Technical Chemistry)

KIT: Karlsruher Institut für Technologie(Karlsruhe Institute of Technology)

KLEAA: Karlsruher Laboranlage zur Ermittlung des Abbrandverhaltens von Abfällen

UMSICHT: Umwelt-, Sicherheits- und Energietechnik(Environmental, Safety, and Energy Technology (UMSICHT))
A_P: Specific area of the particles
$d_{P,50}$: Mean particle size
HR: Heat release rate
IR: Ignition rate
kW: Kilowatt
LHV: Lower heating value
MCR: Mass conversion rate
Mg: Million grams
S_V: Specific surface area
t: Time
u_{RFV}: Reaction front velocity

V_{PA}: Volume flow of primary air
VS_A: Volume flow secondary air
ρ_{bulk}: Bulk density of the initial fuel.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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