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Article

Experimental Investigations of Extracted Rapeseed Combustion Emissions in a Small Scale Stationary Fluidized Bed Combustor

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Abstract: The objective of this study was to observe the combustion process of extracted rapeseed (ER) grist in a stationary fluidized bed combustor (SFBC) and evaluate the chemical compositions of the flue gas emissions. The experimental tests of ER combustion in the 90 to 200 kW (Kilowatt) SFB combustion test facility show that the optimal ER combustion temperature is within the range from 850 to 880° C. Temperature and the concentration of exhausted emissions (e.g. O_2, CO, CO_2, NO, NO_2, SO_2, C_{org}) were measured with dedicated sensors distributed within the combustor, along its height and in the flue gas duct. The experimental results showed that with respect to German emission limits the concentration of SO_2 and NO_x in the flue gas were high whereas that of CO was low. This study furthermore is applicable for the abundant biomass residue resources in Vietnam (rice husk, rice straw, bagasse, cassava residues, coconut shell etc.), which have similar chemical compositions to ER.

Keywords: Combustion, emission, biomass residues, energy.

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1. Introduction

In recent years, many countries have proposed the use of biomass resources to replace conventional fuels (coal, petroleum, natural gas, etc.) in electrical production because they can contribute to global climate regulation as well as solving the problem of agricultural and silvicultural waste utilization [1]. On the other hand, managing biomass energy, which can be stored and produced on demand, is easier than other intermittent renewable energies, i.e. wind-, solar-, or wave-energy [1]. Biomass energy resources have the potential to cover up to 14-15% of total global energy consumption [1,2].

Vietnam is an agricultural country with abundant biomass potential such as e.g. rice husks, rice straw, bagasse, cassava residues, coconut shells, rubber wood, logging residues, straw, and coffee husks. [1,3-6]. Over 50 million tons of biomass is generated yearly in Vietnam, but only 30-40% is used for energy production [1,3,7], most of which is distributed to households for cooking [1] or to mills for cane sugar production (approximately 150 MWth) [1,5]. The potential for biomass energy from wood and agricultural residues in Vietnam is shown in Table 1. In order to contribute to sustainable agricultural and piscicultural development, reduction of greenhouse gases and energy source diversification is necessary. In the present study, it was found that the main physical-chemical properties of rapeseed residues are similar to the residual biomass resources described above. Therefore the successful combustion tests of rapeseed residue in a small scale SFBC reactor imply that the better quality (lower sulphur and nitrogen) residual agricultural resources in Vietnam are also suitable for energetic utilization in a SFBC (for reader convenience, abbreviations are also listed with brief explanations in a Nomenclature at the end of this text) reactor. The work carried out includes the measurement of the net calorific value (NCV) of the feedstock, calculation of the SFBC combustion efficiency and determination of the exhausted emissions.

Table 1. Potential of biomass energy from wood and agricultural residues in Vietnam [1,3,7,8].

Supply and Source of Material	Potential (million tons)	Oil equivalent (million barrels)	Fraction (%)
Natural forest	6.842	2.40	27.36
Artificial forest	3.718	1.32	14.87
Forestry residues	3.850	1.35	15.39
Distributed tree	6.550	2.12	26.19
Industry and fruit-tree	2.400	0.84	9.59
Waste wood	1.649	0.58	6.59
Total woody biomass	**25.01**	**8.61**	**100.0**
Straw, wheat	33.52	7.30	62.69
Rice husk	6.50	2.16	12.17
Bagasse	4.45	0.82	8.32
Other wastes	9.00	1.80	16.83
Total agricultural biomass	**53.47**	**12.08**	**100.0**

According to the World Bank in 2001 Vietnam used only 11% of its currently available bio-energy potential [1,5]. According to [1], the energetic utilization of biomass is associated with substantial advantages and can be achieved at an acceptable cost. The data in Table 2 presents economic values for the use of energy from agricultural residues in comparison to conventional fuel [1]. As indicated in this Table, the "NCV" of conventional fuels is much higher than biomass, i.e. the NCV of 1 kg of anthracite, is more than twice as high as that of rice husks. However, the price of one MJ (Megajoule) of anthracite is approximately 12-18 times higher than one MJ of rice husks. Clearly the feedstock costs of agricultural residues for energetic purposes are economically advantageous. Vietnam can exploit this profuse biomass energy resource to generate heat, power or combined heat and power (CHP) [1].

Within the context of the actual worldwide situation as analysed above, the "Experimental Investigations of Extracted Rapeseed Combustion in a Small Scale Stationary Fluidized Bed Combustor" at the Chair of Environmental Technology (CET), University of Rostock, Germany has an important role in supporting the development of energetic biomass utilization in Vietnam, especially from renewable agricultural biomass residues.

Table 2. Economic comparison of agricultural biomass residues and conventional fuels [1,9].

Source of agricultural residues			**Conventional fuels**		
Fuels[1)]	NCV (MJ/kg)[1)]	\$USD Cent / MJ[2)]	Fuels[1)]	NCV (MJ/kg)[1)]	\$USD Cent / MJ[2)]
Rice husk	14.4	0.014-0.021	Anthracite	31.4	0.255
Rice straw	14.6-15.0	0.027-0.033	Brown coal	11.3	0.442
Maize haulm	14.7	Free of cost	Peat	28.5	0.246
Maize-cob	15.4	Free of cost	Diesel	35.0	0.623
Coffee husk	16.6	Free of cost	Natural gas	40.0	9.100
Bagasse	8.2-16.2	Free of cost			
Wood and waste wood	10.9-16.6	0.102-0.110			
Residues from kapok	11.9	Free of cost			
Coconut shells	17.9	Free of cost			
Sawdust	18.5-19.0	Free of cost			
Residues of cashew nut	24.0-25.0	Free of cost			

1) - source: [1,9]; 2) - status: the year 2006, and source: [10]

In this study the effect of ER on the efficiency of the SFBC combustor and exhaust emissions is investigated. The objective was to determine the optimal combustion conditions and obtain the combustion characteristics and composition of exhaust gases from ER as the basis for the prediction of the combustion characteristics of Vietnam's residual agricultural biomass resources.

2. Results and Discussion

Table 3 shows the general and elemental analyses of Vietnamese residual agricultural biomass in comparison to ER. The general analysis shows that the biomass fuel properties are similar, but ash compositions can be different. Rice husks attract attentions because of their high ash content.

Generallly the sulphur content in biomass fuels is low which leads to a low sulphur dioxide content in the flue gas which will less corrode duct and plant. However, the ER fuel has a relatively high sulphur content and also contains some chlorine. Chlorine and sulphur influence each other. They can be removed by adding Ca-additives, e.g. CaO or $CaCO_3$ as described below [1,11].

$$CaCO_3 + SO_2 + ½\ O_2 \Leftrightarrow CaSO_4 + CO_2$$

(The gypsum is carried out of the reactor and collected in the cyclone with the fuel ash).

$$CaO + 2HCl \Leftrightarrow CaCl_2 + H_2O$$

(The HCl is bonded by the additive process)

The chemical reactions are temperature-sensitive.

Table 3. Chemical compositions and NCV of typical biomass fuels (General and elemental analyses).

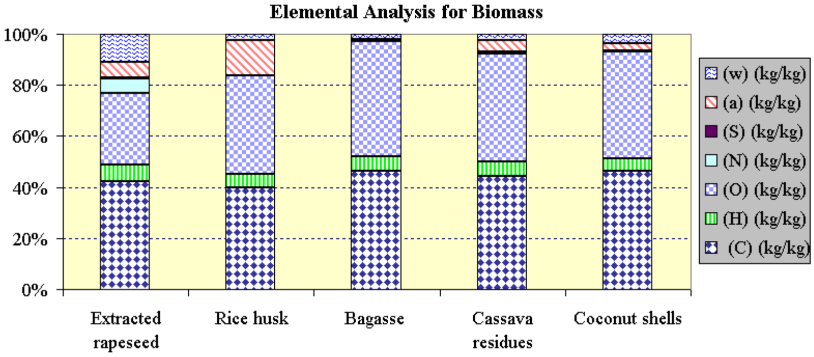
Fuel		**ER** [1)]	**Rice husk** [2)]	**Bagasse** [2)]	**Cassava residue** [2)]	**Coconut shells** [2)]
Components	unit	Value				
General analysis						
Fixed carbon	% mass*	17.20	16.21	2.67	6.87	6.69
Volatile substances	% mass*	76.54	69.87	96.59	88.63	90.31
Ash	% mass*	6.26	13.92	0.74	4.50	3.00
Elemental analysis						
C	kg/kg	0.4235	0.3979	0.4638	0.4434	0.4622
H	kg/kg	0.0636	0.0523	0.0576	0.0576	0.0520
O (as difference)	kg/kg	0.2828	0.3863	0.4519	0.4237	0.4163
N	kg/kg	0.0542	0.0013	-	0.0065	0.0026
S	kg/kg	0.0040	-	-	-	-
Ash	kg/kg	0.0626	0.1392	0.0074	0.0450	0.0300
Moisture	kg/kg	0.1094	0.0230	0.0193	0.0238	0.0369
NCV	kJ/kg	15 983	15 196	16 686	15 942	17 408
Cl	mg/kg	244	1020	260	1970	1670
Ca	mg/kg	59000	4596	60296	166000	59700
K	mg/kg	35000	13500	78200	237000	180000
Mg	mg/kg	38700	2209	59900	29700	15600
P	mg/kg	86200	8649	70600	124000	14700
Cr	mg/kg	1	4	188	5	17
Zn	mg/kg	513	72	1239	1359	160

1)- Fuel of German origin; 2) - Fuels of Vietnamese origin; *- On dry substance basis; "- " below detection limit.

The fuel compositions are described in Table 3. The fuel components vary, depending on the specific fuel type. If the ash and the water are removed from the different fuels, the chemical compositions look very similar. Table 3 and Figure 1 show that the values of the typical fuels are in the following ranges: Carbon: 39.8-46.4%; Hydrogen: 5.2-6.4%; Oxygen: 28.3-45.2%; Nitrogen: 0.1-5.4%; Sulfur: 0-0.4%.

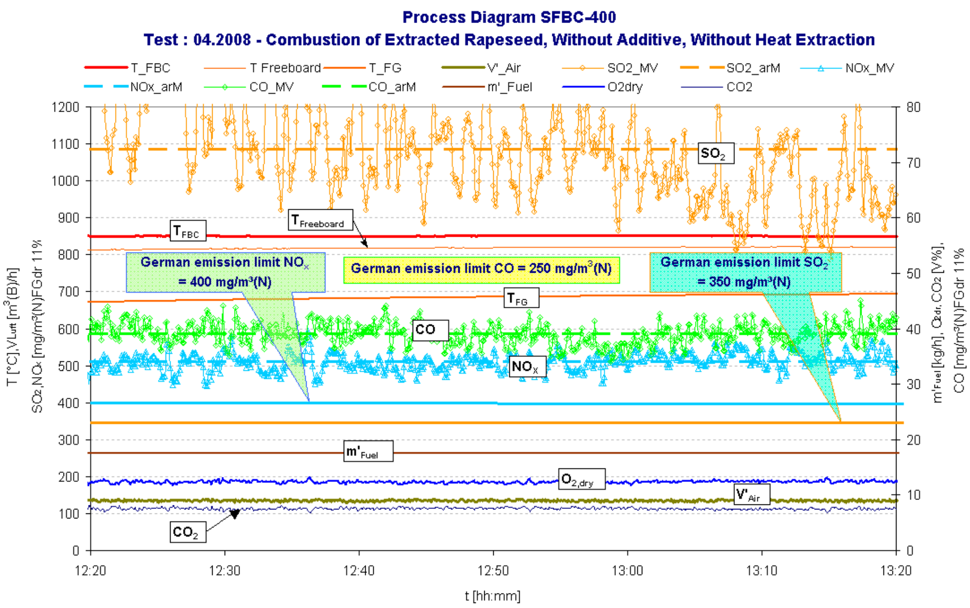
According to [12], ER is a high "nitrogen" fuel (Figure 1). Therefore high NO_x- concentrations can be expected in the flue gas. Steinbrecht [12] states as follows: thermal NO_x vanishes at low fluidized bed temperatures and prompt NO_x is deleted due to the flameless combustion conditions. Therefore the only remaining NO_x source is the fuel nitrogen.

Figure 1. Comparison between the chemical compositions of biomass fuels.



The test run carried out with the ER biomass fuel lead to the conclusion that the Stationary Fluidizing Bed Combustor (SFBC) is suitable for biomass combustion. The important parameters of the process during the tests i.e. combustion temperature and air volume flow, were kept approximately constant. All operation procedures for the tests were chosen in accordance with the know-how of CET and after careful discussion. Figure 2 and Table 4 show the parameters and results of the experiment.

Figure 2. Process diagram of the test run.



FG- Flue gas, MV- Measured value, arM- arithmetic mean

Table 4. Process data and results of the experimental ER combustion tests.

Date		yy.mm	08.04
Measurement start		hh:mm	12:20
Measurement end		hh:mm	13:20
Duration		min	60
Operating Parameters			
Name	**Symbol**	**Unit**	**value**
Height of daybed	h_{Bed}	m	0.95
Mass of bed	m_{Bed}	kg	247.5
Volume of combustion air	V'_{Air}	m^3/h	135
Fuel flow rate	m'_{Fuel}	kg/h	17.5
Fuel capacity	Q'_{Fuel}	kWth	88
Combustion capacity	$Q'_{Combustion}$	kWth	90
Rated output (flue gas)	$Q'_{Flue\ gas}$	kWth	53
Fluidized bed temperature	T_{FB}	°C	850.6
Freeboard temperature	$T_{Freeboard}$	°C	818.8
Temperature of combustion air	$T_{combustion\ air}$	°C	40.9
Humid oxygen	$O_{2\ humid}$	Vol. %	10.8
Dry oxygen	$O_{2\ dry}$	Vol. %	12.4
Emissions (with regard to standard 11 % O_2 content in flue gas)			
Carbon dioxide [(1)]	CO_2	Vol. %	7.5
Maximum Carbon dioxide [(2)]	$CO_{2\ max}$	Vol. %	18.4
Total organic carbon	C_{org}	ppm	-
Carbon monoxide	CO	mg/m³(N)	39
Nitrogen oxides	NO_x	mg/m³(N)	511
Sulphur dioxide	SO_2	mg/m³(N)	1087
German emission limit (TA-Luft 2002)			
Carbon monoxide	CO	mg/m³(N)	250
Nitrogen oxides	NO_x	mg/m³(N)	400
Sulphur dioxide	SO_2	mg/m³(N)	350
Emissions as measured (influenced by dry oxygen content)			
	Unit	**Value**$^{*)}$	**value**$^{*)}$
Dry oxygen ($O_{2\ dry}$)	Vol. %	10,7	13,2
Carbon monoxide (CO)	mg/m³(N)	34,8	44,2
Nitrogen oxides (NO_x)	mg/m³(N)	446	594
Sulphur dioxide (SO_2)	mg/m³(N)	786	1582

*)- The lower and higher value to indicate the range of measured emissions.

$$^{(1)}CO_{2,} = \frac{V_{CO_2}}{V_w} = \frac{V_{CO_2}}{(V_{CO_2} + V_{SO_2} + V_{N_2} + V_{O_2})} \ ; \ ^{(2)}CO_{2,\max} = \frac{V_{CO_2}}{V_{dr}} = \frac{V_{CO_2}}{(V_{CO_2} + V_{SO_2} + V_{N_2})} \ ; \ (O_2 = 0)$$

with: V_w- humid flue gas volume; V_{dr}- dry flue gas volume and $V_w = V_{dr} + V_{H_2O}$

The flue gas emission investigation results are shown in Table 4. The concentration of exhaust emissions are based on the comparison with German emission limit (with concentration of $O_{2,dry,basis}$ = 11 Vol. %).

The results in Table 4 show, that the concentration of NO_x- and SO_2-emission in the flue gas exceeded the German emission limit (TA-Luft 2002 [13]), (TA-Luft 2002: *Technische Anleitung zur Reinhaltung der Luft, 2002*), (Limit of TA-Luft 2002 are 400 mg/m^3 (N) and 350 mg/m^3 (N) flue gas, corresponding , with O_{2dry} = 11 Vol. % [13]).

- The relative high NO_x concentration appears because of the relatively high oxygen concentration during the combustion process and especially high concentration of nitrogen in fuel (approx. 5.4%). It can be minimized if the oxygen concentration is reduced by higher fuel mass rate, e.g. by heat-extraction from the bed or by recirculation of “cold” cleaned flue gases.The value of N_2O however was not measured because it is expected to be very very low for solid biomass fuel combustion [12].
- The high SO_2 content in the flue gas is the result of the high ER feedstock sulphur content of 0.4%, which is around four times as high as most other agricultural biomass residues.

The fuel-related acid sulphur dioxide (SO_2) emissions can be abated by the in-situ procedural additive of $CaCO_3$ to the process [14]. Therefore slaked lime is applied to the reactor. This additive will react with the SO_2 to gypsum and leave the combustion chamber over the freeboard together with flue gas and fuel ash. Typically the dust mix is separated with cyclones and a mechanic precipitator (bag house filter) to keep dust emissions within the prescribed limits. Several methods are known at the CET to minimize nitrogen oxides in the flue gas. Generally suited are the methods of minimizing of oxygen concentration in the flue gas by using a fluidizing bed cooler or alternatively flue gas recirculation and the Selective Non-Catalytic Reduction (SNCR) with the reagent urea or ammonia solution. The choice of the measure depends on the height of the emission, the necessary level of abatement, the energy recovery concept, as well as the required legal limits and the economy of the plant.

- Interestingly the CO-emission concentrations were remarkably low in comparison to the German emission limit, especially during the combustion of extracted rapeseed. This indicates a clean burn out in the SFBC combustion chamber.
- The ash-melting-problem (ash sintering can cause agglomeration of the bed material leading to severe slagging and fouling of the SFBC reactor and finally termination the bed fluidization) can be solved by decreasing the bed temperature below the critical limit. The critical temperature limit depends on the sintering temperature of the biomass ash, and is often below 850° C for residual agricultural biomass fuels. The ER test run (Figure 2) shows that a clean combustion in the SFB reactor is possible at temperatures below 850° C. This can be verified by the very low concentrations of carbon monoxide (CO) and the sum parameter C_{org} (gaseous hydrocarbons) measured during the test run (Figure 2 and Table 4). Thus a steady-state and stable combustion with a complete fuel conversion can be achieved in the combustions chamber at suitable temperatures for residual biomass combustion.

A very good burn-out at low temperature is possible in the SFBC reactor due to the main combustion mechanism, known in the in chemical engineering literature as the ‘*triple T*’ [11,14]:

- ***T***urbulence (good mixing of the feedstock with the bed material)

• ***T***emperature (low, so low thermal NO_x, and suitable for biomass, but still complete combustion)
• ***T***ime (high residence time at appropriate temperature window to ensure complete combustion)

The cyclone ash analysis is presented in Table 5. The results show that, the alkali content K, Mg Ca in the ER ash is significant. High alkali content is an indication of low ash sintering temperature, and underlines the necessity for low combustion temperatures.

Table 5. Cyclone ash analyses.

Properties	Value (mg/kg ash)	Properties	Value (mg/kg ash)	Properties	Value (mg/kg ash)
K	41,200	Al	902	Cu	68
P	54,000	Fe	8,410	Ni	380
Mg	27,800	Mn	520	Pb	360
Ca	71,496	Cd	<1	Zn	240
Na	945	Cr	365	Sr	144
				Ti	35

The results of this research are generally applicable for the utilization of biomass in a stationary fluidized bed combustion for heat generation and utilization, for example in: combined heat and power plants, processing plants for cassava starch, and/or for the simultaneous drying of other agricultural products. This simple robust technology is well suited for application in developing countries such as Vietnam.

The technical parameters of the combustion process with ER fuels can be applied to the combustion of Vietnamese fuels because:

- the fluidized bed combustion temperature will be similar,
- the combustion air flow rate will be similar and
- the concentration of dry oxygen in flue gas (air/fuel ratio) will be similar.

The implications of these similarities for the combustion of Vietnamese fuels are that:

- the amount of heat available for energetic processes will also be similar and
- the NO_x emission is expected to be significantly lower.

On the other hand due to the lower fuel sulphur and nitrogen contents in Vietnamese biomass fuels:

- the SO_2 emissions are expected to be a lot lower and within the TA-Luft 2002 emissions limits and
- the CO- emission values will be similar.

3. Conclusions

The combustion test of extracted rapeseed in SFBC was carried out at T_{FB}= 850° C and a fuel mass flow of 17.5 kg/h. This corresponds to fuel primary energy of 88 kW. Experimental results with non-influenced SFBC combustion have shown that the concentrations of NO_x, and SO_2 in the flue gas are higher than the legal limits of TA-Luft 2002, whereas the CO concentrations were lower. The basic level of carbon monoxide (CO) is significantly low [39 mg/m^3 (N)], which indicates clean and efficient combustion, but especially the concentration of sulphur dioxide (SO_2) emission [1,087 mg/m^3 (N)] is significantly higher than the value limit of TA-Luft 2002. The removal of SO_2 during SFB biomass combustion is the subject of ongoing investigation at the University of Rostock, Chair of Environmental Technology. Previous experience indicates that the measured parameters of the combustion process such as combustion "Temperature", "Turbulence", and combustion "Time" have a strong effect on emission of CO, C_{org} and SO_2 whereas NO_x depends on the fuel characteristics, combustion temperature and available oxygen concentration.

The flue gas heat energy after the SFBC reactor can be used for heating and other technological purposes. Typical example is drying of agricultural products. The SFBC process is very useful for the application of biomass fuels, and is deemed suitable for the residual agricultural biomass in Vietnam and other developing countries where the opportunities for energetic utilization of residual biomass are very limited.

The result from this study can be evaluated as a work with significant scientific and practical applications for Vietnam in the future. It is possible to utilize the results as a model for the combustion of similar solid biofuels in Vietnam, although the NO_x and SO_2 emissions are expected to be a lot lower. Especially future attention should be focused on combined production of thermal and electric energy-CHP. Based on the combustion tests, we judged the SFBC to be very suitable for the combustion of extracted rapeseed.

4. Materials and Methods

4.1. The Properties of Experimental Materials

The experimental fuel tested here is ER (Figure 3a). This feedstock has very similar fuel properties such as density, according to ISO and net calorific value (NCV) and physical- chemical properties such as carbon (C), oxygen (O), hydrogen (H), ash (a) and water (w) to the biomass residues (i.e. rice husk, bagasse, cassava residues and coconut shells) available in Vietnam (Figure 3b-3e). The combustion test results of ER can therefore be utilized as a model for the combustion characteristics of residual agricultural biomass of Vietnam, when the lower nitrogen (N) and sulphur (S) content is taken into account. The ER fuel properties have been analysed and compared to the analysis results of the residual biomass of Vietnam (see Table 3, Figure 1).

Figure 3. Experimental materials (a- extracted rapeseed), and residual biomass of Vietnam (b- rice husks, c- bagasse, d- cassava residues, e- coconut shells).

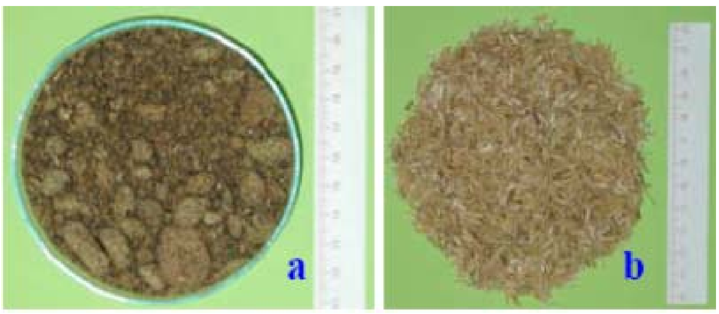


Figure 3. Cont.

4.2. Presentation of the Experimental Plant

The analyses and combustion experiment were conducted using the facilities at the CET, University of Rostock, Germany. Figure 4 shows the experimental equipment, and Figure 5 shows the technological flowsheet of SFBC and its auxiliary equipment. This system utilizes quartz sand (mean size in the range from 0.1 to 2.0 mm, height of daybed is 0.95 m, mass of bed is 247.5 kg) as inertial fluidization material to realize the clean SFBC combustion process. The combustion air is supplied by a roots blower (volume flow of combustion air is 135 m^3 (N)/h and the superficial velocity is 1.6 m/s), to realize the high pressure differences (app. 13 kPa, for 0.95 m height of "quite bed"). The combustion air can be either directly supplied to the reactor or pre-heated by an air/flue gas air-heater.

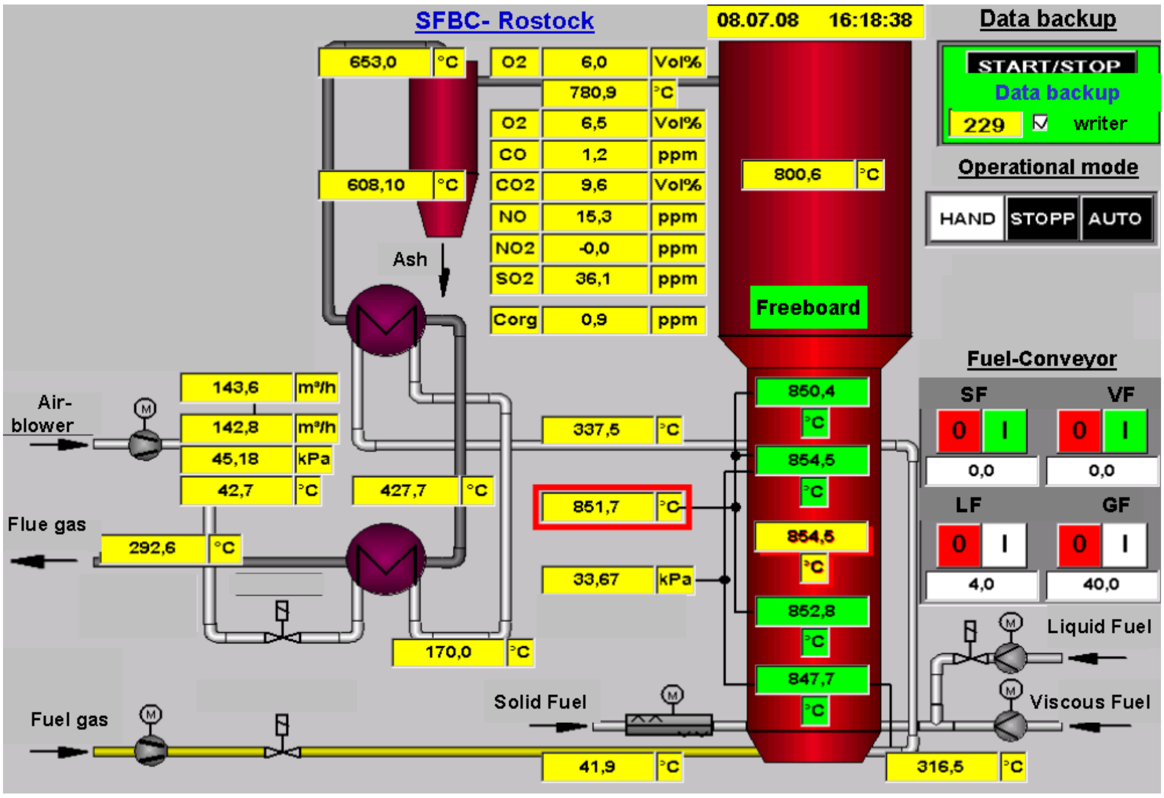
Figure 4. Experimental equipment SFBC at the CET Rostock University, Germany [12,14].

The preheating of the plant during the start-up phase is realized with methane delivered from the municipal supply network. The methane is fed into the reactor and ignited by a small propane burner. During start-up the air-gas mixture is combusted above the bed. As the bed becomes fluidized the combustion process is immersed. The bed particles are gradually heated up. When the mean bed temperature had reached and passed the self ignition temperature of the methane, its feed from the network stops and the propane burner is unplugged. Then the methane inlet is opened again and the methane is fed into the reactor from the bottom where it is self-ignited without an additional combustor. When the plant had reached operating steady state temperature and the heating value of the fuel to be incinerated is high enough there is no need of additional methane. The methane feed is then stopped and additional combustion air is fed through the methane inlet (through the nozzle grid).

The SFBC reactor has the capability to utilize nearly all fuels (gas, liquid, solid or mixtures) with a wide range of fuel properties. The auxiliary system equipment must be adjusted for the particular fuel properties in the system. There are two screw feeders: solid fuel screw feeder and an additive screw feeder. The solid fuel screw is controlled by a PI-type governor which is connected with the main process computer [1].

The experiments were completed with the plant SFBC-400 as shown in Figure 4. Fuels such as gas, liquid, solid or the mixtures thereof can be tested with this plant. The test parameters of the combustion process were adjusted with the process computer [1].

Figure 5. The technological flow sheet of SFBC at the CET, Rostock University, Germany [1].



SF- Solid Fuel, VF- Viscous Fuel, LF- Liquid Fuel, GF- Gas Fuel.

The additive screw feeder can be used to transfer not only bed material but also different additives such as limestone or urea and fuels. Additionally there are two pump-systems which can supply liquid fuel: one for low viscous fuel (e.g. bio-diesel product) and another for high viscous fuel (e.g. sewage sludge) [1].

The system is equipped with a great number of valves (either automatically or manually driven), thermocouples, flow meters and pressure gauges. Their entire outgoing signals are collected and then transmitted to the main computer. After that, they are registered by a special software developed at the CET. The main computer transmits signals to two monitors: major monitor (usually used by an operator to review different data and to manipulate the system) and minor monitor (which is always used to show a scheme of the system with actually measured signals). They show on-line changing parameters such as temperature of the bed, temperature of the freeboard, volume flow of air and fuel etc. (Figure 5) [1].

The system is equipped with three special tools for gas analysis (Figure 6). The first is called 'ZIROX', giving on-line signals about the oxygen partial pressure (converted to concentration) in the humid flue gases. The second tool analyzes and measures the concentrations of exhaust emissions in the dried flue gas, such as oxygen (O_{2dry}), carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and organic carbon compounds (C_{org}) (Figures 5 and Figure 6). The third system (coupling of gas-chromatograph and mass-selective detector) enables the detection and determination of the concentrations of further organic pollutants [1].

Figure 6. The systems for measurements of gas components in flue gas and for gas analyzes at the Chair of Environmental Technology, University of Rostock, Germany [1].

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Nomenclature

$USD Cent:	US-Dollar Cent
CET:	Chair of Environmental Technology
CHP:	Combined Heat and Power
ER:	Extracted Rapeseed
kW:	Kilowatt (s)
kWth:	Kilowatt thermal
MJ:	Megajoule
NCV:	Net Calorific Value

SFBC: Stationary Fluidized Bed Combustor
TA-Luft 2002: Technische Anleitung zur Reinhaltung der Luft, 2002

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