



# Alkali retention/separation during bagasse gasification: a comparison between a fluidised bed and a cyclone gasifier

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Received 10 November 2000; accepted 26 June 2001

## Abstract

Biomass fuelled integrated gasification/gas turbines (BIG/GTs) have been found to be one of the most promising technologies to maximise electricity output in the sugar industry. However, biomass fuels contain alkali metals (Na and K) which may be released during the gasification processes and cause deleterious effects on the downstream hardware (e.g. the blades of gas turbines). Much research has therefore been focused on different kinds of gas cleaning. Most of these projects are using a fluidised bed gasifier and includes extensive gas cleaning which leads to a high capital investment.

Increasing alkali retention/separation during the gasification may lead to improved producer gas quality and reduced costs for gas cleaning. However, very little quantitative information is available about the actual potential of this effect. In the present work, comparative bench-scale tests of bagasse gasification were therefore run in an isothermal fluidised bed gasifier and in a cyclone gasifier to evaluate which gasification process is most attractive as regards alkali retention/separation, and to try to elucidate the mechanisms responsible for the retention.

The alkali retention in the fluidised bed gasifier was found to be in the range of 12–4% whereas in the cyclone gasifier the alkali separation was found to be about 70%. No significant coating of the fluidised bed's bed material particles could be observed. The SEM/EDS and the elemental maps of the bed material show that a non-sticky ash matrix consisting of mainly Si, Al and K were distributed in a solid form separated from the particles of bed material. This indicates the formation of a high temperature melting potassium containing silicate phase, which is continuously scavenged and lost from the bed through elutriation. © 2001 Elsevier Science Ltd. All rights reserved.

**Keywords:** Bagasse; Fluidised bed gasifier; Cyclone gasifier; Alkali retention

## 1. Introduction

The production of electricity from biomass offers an environmentally friendly alternative to the use of

fossil fuels. A biomass fuelled integrated gasification/gas turbine (BIG/GT) process has the promise of being able to produce electricity with a high efficiency and low emissions and at competitive cost if the biomass fuel is available at low cost. Thus, BIG/GT technologies could also be used to maximise the electricity output in the sugar industry in developing

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countries [1]. However, gas turbines are generally designed to run on very clean fuels such as natural gas or light petroleum. Biomass fuels, on the other hand, have relatively high ash contents with ash forming elements that are especially prone on forming compounds with deleterious effects on the downstream hardware. Some of the ash forming elements, such as alkali elements (K + Na), may form corrosive species, which are thought to be the main cause of high temperature corrosion of gas turbine blades [2]. Deposition of ash compounds and corrosion caused by these will lead to increased maintenance costs and reduced equipment availability.

Therefore, a considerable amount of bench- and pilot-scale research have been conducted in Europe and US to develop methods for clean up of the producer gas from biomass gasification to suit operation of a gas turbine. Most of these projects are using a fluidised bed gasifier (FBG) and includes extensive gas cleaning which leads to a high capital investment.

In the FBG, the excellent heat and mass transfer lead to relatively uniform temperature throughout the bed. Therefore, the temperature can be kept relatively low (about 900°C), to prevent ash melting. This temperature range is below the fusion temperature of most types of ash, therefore slag and clinker formation can be avoided.

Luleå University of Technology and Energy Technology Centre in Piteå (ETC) are investigating a new approach for avoiding excessive amounts of alkali compounds in the hot gases entering the gas turbine. Biomass powder is gasified in a combined cyclone separator and gasifier operated at a relatively low temperature. The advantage with this technique is that the process conditions might be kept at a level where the volatilisation of corrosive elements such as sodium and potassium may not occur. The corrosive compounds would then remain solid in the char particles, which could be separated and combusted separately.

Although several indications are available on significant retention of alkali metals in the bottom residues of different gasifiers, surprisingly little work have been performed to quantify the effect. Previous results [3], from the cyclone gasification of wood powder have indicated alkali separations in the range 40–60%. Turn et al. [4], found 40–80% of the alkali metals in the tested biomass fuels to be retained in the bed as a bottom residue in the FBG. Mojtabedi et al. [5] however

found that 100% of the alkali left the bed for FB gasification of peat. It, therefore, appears that more studies of biomass gasification in fluidised bed gasifier (FBG) are required to better understand the long-term implication of inorganic accumulation of alkali compounds in the bed.

Until now, comparative tests where the same fuel has been gasified in a CG and in a FBG, have not been reported. In the present work, a comparison between CG and FBG was therefore carried out to determine the extent of, and differences in, the alkali retention between the two technologies, using bagasse as a feedstock. A chemical equilibrium analysis was used to discuss the fate of alkali metals during gasification.

## 2. Fuel characteristics and preparation

Table 1 shows the characteristics of the bagasse used in the present experiments. The main inorganic elements found in the bagasse fuel are Si, Ca, Fe, Al, K and Mg. These elements account for about 93% of the ash calculated as pure elements. Potassium (K) is present in about 60% of the amount of calcium (Ca), but is expected to cause more problems through its corrosive properties. Sodium is present in a small percentage (25%) compared to potassium. The amount of SiO<sub>2</sub> in the inorganic part of the bagasse fuel is about 72%. Often bagasse fuel is contaminated by soil during harvesting and transportation, which is difficult to distinguish from the ash forming elements of the fuel itself.

The ash elements content in the fuel ash are very important for the assessment of the possibilities to use bagasse as a fuel for a gas turbine. Most of the data collected from different countries [6] indicate an ash content of bagasse fuel of about 2%. The higher ash content found in the bagasse used with this experiment could be explained by different harvesting methods that lead to more contamination by soil.

The low bulk density and cohesive character of crushed bagasse powder initially created a great number of difficulties concerning the feeding of the fuel to the cyclone. To improve the characteristics of the fuel and to eliminate the feeding problems associated with the crushed bagasse, the crushed bagasse was pelletised and then ground. It was found that this treatment made the fuel more homogeneous and the bulk

Table 1  
Bagasse fuel characteristics<sup>a</sup>

Description		
Heating value		
HHV (dry fuel)		18.2
LHV (dry fuel)		17.02
Elemental analysis of dry fuel, wt%		
Carbon C		45.2
Hydrogen H		5.4
Oxygen O		41.8
Nitrogen N		0.2
Sulphur S		0.02
Chlorine Cl		0.03
Volatiles		79.6
Ash (dry basis) (wt%)		7.7
Ash composition (wt%)		
SiO <sub>2</sub>		72.29
Al <sub>2</sub> O <sub>3</sub>		7.99
CaO		4.16
Fe <sub>2</sub> O <sub>3</sub>		6.16
K <sub>2</sub> O		4.49
MgO		2.34
MnO <sub>2</sub>		0.14
Na <sub>2</sub> O		0.95
P <sub>2</sub> O <sub>5</sub>		0.93
TiO <sub>2</sub>		0.55
Size distribution		
Particle size (mm)	Crushed bagasse	Ground bagasse pellets
> 2.0	0%	1%
1.0–2.0	2%	23%
0.5–1.0	23%	23%
0.25–0.5	50%	25%
0.125–0.25	11%	16%
0.1–0.125	6%	2%
0.071–0.1	3%	2%
0.04–0.071	3%	5%
< 0–0.04	3%	3%
Bulk density (kg/m <sup>3</sup> )	128	485

<sup>a</sup>Moisture contents: Ground bagasse pellets for CG 3.9%; bagasse pellets for FBG 12.8%.

density increased from 128 to 485 kg/m<sup>3</sup>. For more details, see [7]. The size distributions determined by sieving are shown in Table 1.

For the FBG tests, the bagasse pellets were cut to small pieces in order to avoid feeding fluctuations and defluidisation problems caused by large and slow reacting bagasse particles.

### 3. Experimental equipment

#### 3.1. Bench-scale isothermal atmospheric fluidised bed gasifier

A schematic diagram of the bench-scale isothermal atmospheric fluidised bed gasifier is shown in Fig. 1. The feeding system consists of a fuel feeding bin and an electrical vibrator. The vibrator is used to control the fuel feeding rates and to reduce the fluctuations of the fuel flow.

The fluidised bed reactor tube is made of stainless steel. The reactor tube is 10 cm in diameter for both reactor bed and freeboard and 2.30 m in height. A perforated stainless steel distributor plate with 1% open area and total of 90 holes is used to fluidise a bed of quartz sand. The quartz sand used as a bed material was initially sieved to sizes between 250 and 355  $\mu\text{m}$ , Table 2.

Air was used as a fluidising agent. For a homogeneous temperature profile, the freeboard tube and the bed section were externally heated with a set of Kanthal Fibrothal cylindrical and half-cylindrical heating elements controlled by Eurotherm temperature controllers. An air preheater was employed to control the bed temperature.

Bed temperatures were measured by shielded thermocouples (type S). A vertically moveable thermocouple (type N) was used for measuring the producer gas temperature at different locations in the freeboard. Measured gas temperature profiles for different operating conditions showed maximum temperature deviations of  $\pm 20^\circ\text{C}$  in the whole freeboard section.

#### 3.2. Atmospheric cyclone gasifier

A schematic diagram of the atmospheric cyclone gasifier is shown in Fig. 2. The fuel system consisted of a storage bin, a screw conveyor, a fuel feeding bin with screw feeders in the bottom and two chutes (downcomers). The two downcomers are connected to the cyclone gasifier and to the feeding bin.

The fuel powder is transferred from the storage bin to the feeding bin by means of a single screw feeder and further from the fuel-feeding bin by means of two double screw feeders, into the two downcomers. Frequency adjusting devices are used to control the speed of the motors that drive the feeding screws.

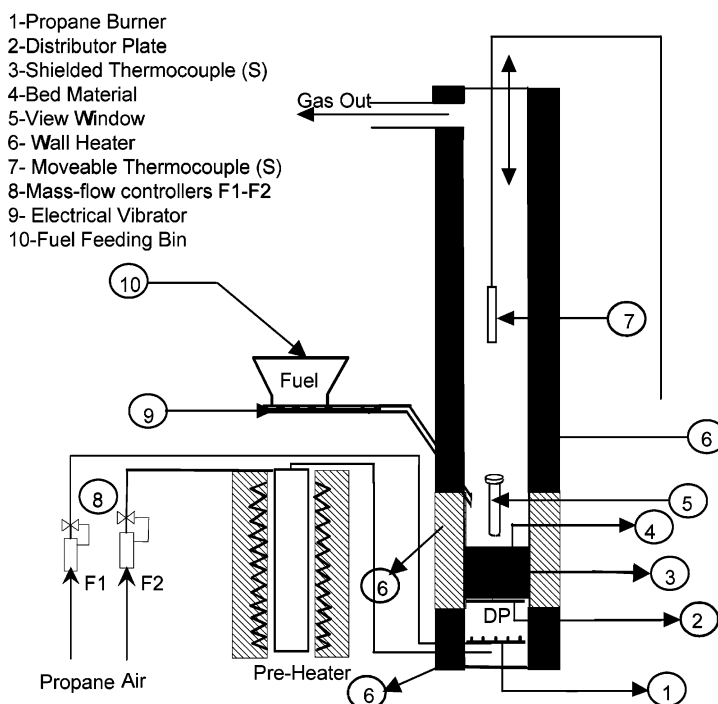


Fig. 1. A schematic diagram of bench-scale isothermal atmospheric fluidised bed gasifier.

Table 2  
Properties of bed material (quartz)

Bed material	
Particle diameter ( $\mu\text{m}$ )	250–355
Composition of inorganic part (wt%)	
$\text{SiO}_2$	96.10
$\text{Al}_2\text{O}_3$	0.25
$\text{CaO}$	0.10
$\text{Fe}_2\text{O}_3$	0.31
$\text{K}_2\text{O}$	0.11
$\text{MgO}$	0.07
$\text{MnO}_2$	0.00
$\text{Na}_2\text{O}$	0.05
$\text{P}_2\text{O}_5$	0.01
$\text{TiO}_2$	0.11

The fuel mass flow is controlled by the speed of the screws in the feeding bin which is recorded on a data logger. The feeding rate as function of screw speed was determined by calibration tests.

Before the powder goes into the downcomers, it must pass through a brush-like device, which was

introduced in order to reduce the fluctuations of the fuel flow to a minimum. The brushes were installed at the end of each feeder screw above the inlet to the downcomers. For more details, see Gabra et al. [7].

The powder falls by gravity through the downcomers to the suction chambers of the fuel injectors, where the fuel is sucked into the cyclone through two opposite injectors entering the cyclone in a tangential direction. Pressurised steam was used to drive the injectors. The injectors are used also as suction pumps to suck the air required for gasification. The inlets have a circular cross-section with a diameter of 28 mm.

The cyclone gasifier is made of temperature-resistant stainless steel. The cyclone gasifier, which is designed as a standard cyclone separator, works as a particle separator as well. The cyclone is mounted vertically standing on a dust bunker at the cyclone bottom where the char is separated. The dimensions of the tested cyclone gasifier are shown in Fig. 3.

During the gasification tests, cyclone gas—and wall temperatures and the flows of air and steam are measured. Six wall temperatures of the cyclone are

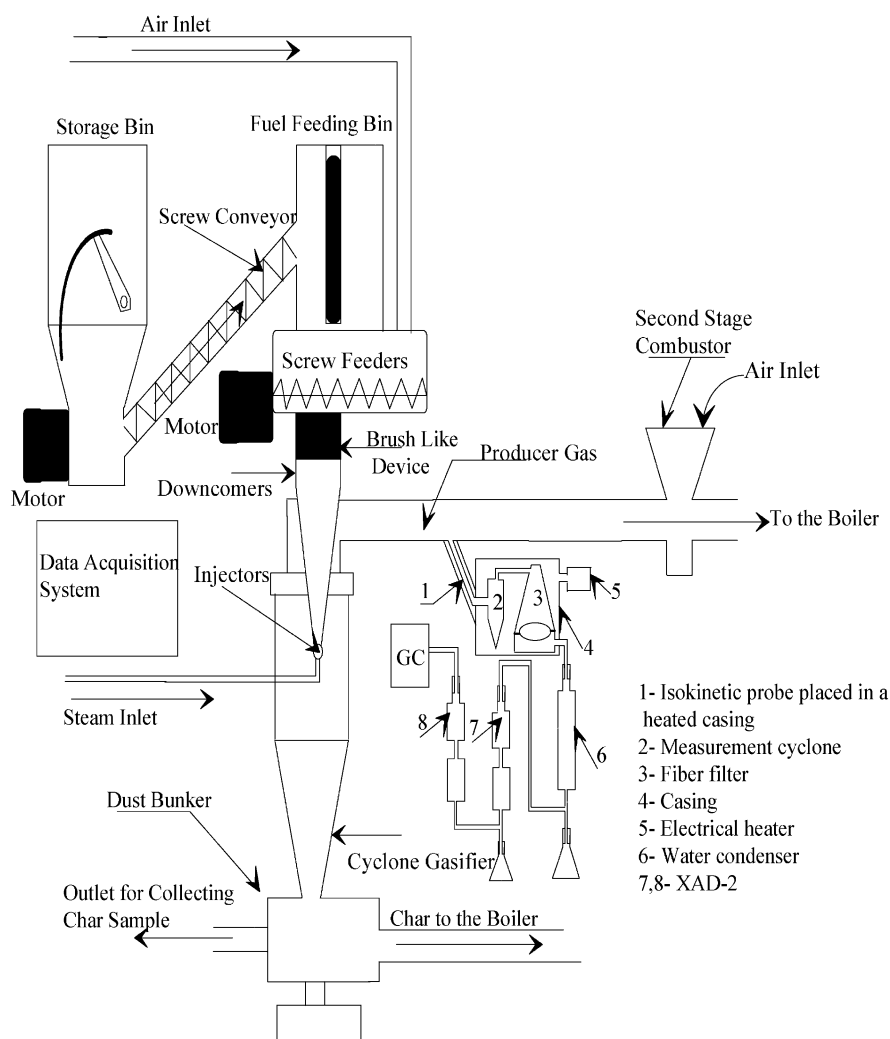


Fig. 2. Schematic diagram of a two stage atmospheric gasification/combustor.

measured with sheathed thermocouple type K, attached vertically. Three measure the upper wall temperature at the level of the cyclone inlet and three measure the lower wall temperature where the cylindrical and conical part of the cyclone meet. A type N sheathed thermocouple with radiation shield is used for gas temperature measurements at the cyclone outlet. Air and steam flows are measured with pressure difference over orifice plates. The pressure difference is measured with an electronic pressure gauge and the flow corresponding to this difference is calculated according to ISO 5167-1:199 (E).

## 4. Experimental procedures

### 4.1. Atmospheric fluidised bed gasifier

In preparation of the gasification test, fresh bed material and fuel were weighed and placed in the bed reactor and the fuel-feeding bin, respectively. The tests were started by charging the bed reactor with the bed material (quartz) and pre-heating it by a propane burner and the wall heating elements before injection of the bagasse fuel. The freeboard was heated with the wall heating elements.

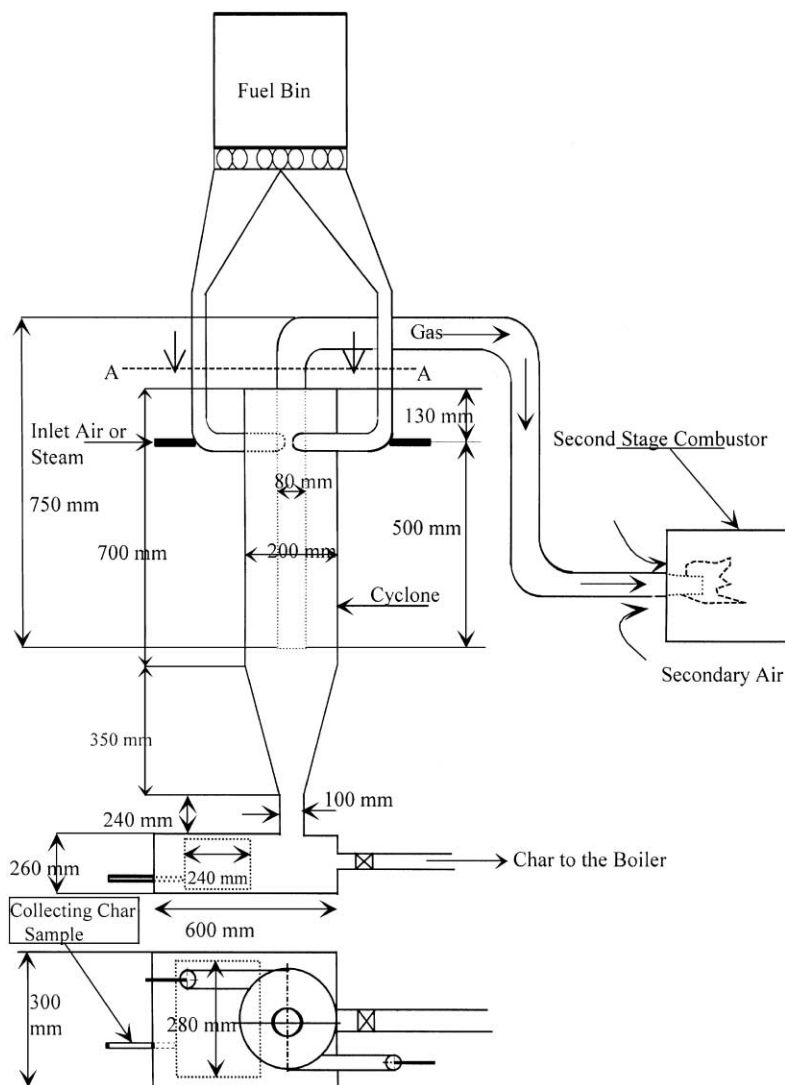


Fig. 3. Cyclone dimensions—side view and top view A—A of the experimental set-up.

When the fluidised bed reactor and the freeboard reached a homogenous temperature of about  $850^{\circ}\text{C}$  the propane burner was cut off and then the feeder was turned on. The rate of fuel flow to the reactor was adjusted to produce the desired equivalence ratio of 0.34. A steady air flow of 2.85 kg/h was maintained during the gasification tests to keep the same residence time and steady fluidisation velocity. The controlled wall heating elements were continuously used

during the experiment to keep the freeboard and the bed reactor at constant temperature<sup>1</sup> of  $850^{\circ}\text{C}$ . The

<sup>1</sup> Earlier studies for determination of bagasse agglomeration in a fluidised bed gasifier—sand bed shows that the initial agglomeration temperature of bagasse is above  $1000^{\circ}\text{C}$ , higher than the gasification temperature used for this study. For more details, see [8].

resulting freeboard velocity at this temperature will be 0.13 m/s.

A number of trial tests and replicating of some experiments have been done to determine the gasification test of stable conditions at a temperature of 850°C. At this temperature the gasification tests of stable condition have been obtained with feeding rate of 1.75 kg/h and equivalence ratio of 0.34.

The producer gas was generated after a few minutes from the injection of bagasse fuel. The producer gas leaves through the top outlet of the freeboard tube. Collection of samples from the bed materials begun when the system had reached a steady temperature.

Two gasification experiments has been conducted. The duration of the first experiment was 1.37 (h) and the second 12.5 (h). At the end of the first experiment, a bed sample was collected. For the second experiment, seven samples were collected. One of these samples was collected at the end of the experiment. The other six samples of the bed material were collected throughout the experimental runs using an air-cooled suction probe, equipped with a cyclone separator. The three samples were collected with an interval of one hour, the following two samples were collected with an interval of three hours and then sample six was collected just before termination of the experiment.

At the end of each test, fuel and airflow to the reactor and the *external* heater were shut simultaneously. The reactor bed was rapidly cooled by injecting nitrogen into the bed to minimise weight loss due to gasification of the hot bed material. After the system had cooled the last sample was collected. The remaining bed material was removed from the fuel reactor bed and the bed was weighed. Also the remaining fuel in the fuel-feeding bin was weighed to give a more accurate value for the feeding rate.

Each of the collected bed samples was weighed and analysed to determine the alkali retention in the bed reactor as a function of time. The contents of ash element in the bed samples were determined by chemical analysis. The seven samples that were collected during the second gasification experiment have also been analysed with scanning electron microscopy (SEM) combined with energy dispersive spectroscopy analysis (EDS).

#### 4.2. Atmospheric cyclone gasifier

In the cyclone gasifier, the experiments were started by pre-heating the cyclone with a propane burner before injection of the bagasse powder. The fuel injection was started when the wall temperature was about 850°C, after which the heat necessary for the reactions to proceed will be generated from the reactions themselves.

The equivalence ratios for the gasification tests are determined by the temperature limits of the cyclone gasifier. The cyclone wall temperature limits for stable gasification temperature were found to be in the range of 650–950°C. This interval of the allowable operation temperature of the cyclone gives equivalence ratios ranging from 0.25 to 0.21. This interval of the equivalence ratios gives gas temperature on an average of 850°C.

A feeding rate of 39 kg/h was used for bagasse gasification tests in the cyclone gasifier. The feeding rate was controlled by adjustment of the speed of the feeder screws. The desired equivalence ratios were produced by adjustment of the air flow. It was found impossible with the cyclone gasifier set-up to use equivalence ratio similar to that used with fluidised bed gasification experiment. The gasification test was conducted at an equivalence ratio of 0.25, with two replicate runs.

The producer gas was generated after a few minutes from the injection of bagasse fuel and it leaves through the top outlet of the cyclone. After about 15 min the system reached stable conditions and was running smoothly.

When the cyclone was running at steady state conditions with stable temperature and at a specific equivalence ratio, a char sample was collected from the bottom residue. The char samples were stored in collecting vessels with an airtight cap to minimise weight loss due to combustion of the hot char.

#### 4.3. Chemical analysis

Chemical analysis of fuel, samples of cyclone char and bed materials samples of the fluidised bed were performed by SGAB (Luleå Technical University, Sweden). The samples were dried at 105°C according to the Swedish Standard SS 028113, and the ash content determined at 550°C, according to the

ASTM D3682, modified to be used with biomass fuels. The ash sample of 0.125 g is fused with 0.375 g  $\text{LiBO}_2$  and dissolved in dilute  $\text{HNO}_3$ . Determination of elemental concentration is done by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

## 5. Experimental results

### 5.1. Alkali retention/separation

Table 3 shows the ash forming elements in bagasse fuel and gasification residue samples from bagasse gasification in FBG and CG in g/kg (fuel). Table 4 shows compositions of the ash forming compounds in the gasification residue produced during the gasification tests in CG and FBG and the bagasse fuel, calculated as oxides. The data for the FB gasifier refer to the results of analysis of the entire inorganic part of the bed.

The alkali retention/separation is defined as alkali retained in the bed reactor of FB gasifier or alkali separated with char at cyclone bottom divided by the alkali input with the fuel. The alkali retained in the bed reactor of the FB gasifier was calculated from the difference between alkali content in the bed material at time ( $t$ ) and alkali content of the fresh bed material (quartz) at the beginning of the experiment.

The bagasse gasification experiments (1 and 2) in the FBG have shown that the alkali retention calculated from the observations will be different if the retention is calculated from bed samples and not from analysis of the entire inorganic part of the bed. In the long run gasification experiment, the bed sampling results show retention dropping from about 3% after 1 (h) to about 2% after 12.5 (h). Analysis of the entire inorganic part of the bed shows higher retention, in particular after the short experiment. Retention calculated from these observation are 12% after 1.4 (h) and 3.6% after 12.5 (h), see Fig. 4.

Table 3  
Ash forming elements in bagasse fuel and gasification residue samples from bagasse gasification in cg and fbg in g/kg (fuel)

		39	39	1.66	1.71
Fuel rate (kg/h)		39	39	1.66	1.71
Total run time (h)		6	6	1.37	12.5
Bed temp ( $^{\circ}\text{C}$ )		850	850	850	850
Air flow (kg/h)		47	47	2.85	2.85
Equivalence ratio (ER)		0.25	0.25	0.34	0.34
		Gasification residues			
		Replication 1	Replication 2	Experiment 1	Experiment 2
Ash forming elements (g/kg) (fuel)	Fuel	CG	CG	FBG	FBG
Si	23.83	14.50	14.18	4.32	15.26
Al	1.46	1.03	1.01	0.21	0.06
Ca	1.84	1.29	1.26	0.22	0.09
Fe	1.33	0.96	0.93	0.30	0.15
K	1.04	0.80	0.79	0.19	0.05
Mg	0.95	0.64	0.63	0.12	0.04
Mn	0.58	0.04	0.04	0.06	0.01
Na	0.27	0.13	0.13	0.00	0.00
P	0.13	0.09	0.09	0.02	0.01
Ti	0.26	0.15	0.15	0.24	0.01
Cl	0.28	0.03	0.03	0.06	0.10
K + Na separated with char as % of K + Na input with fuel		71%	70%	12%	3.6%
K + Na in gas, mg/kg-wet gas		154	156	265	285



Table 4

Comparison of the inorganic part in the fuel and gasification residue in cyclone gasifier and fluidised bed gasifier

Fuel rate (kg/h)	39	39	1.66	1.71
Equivalence ratio (ER)	0.25	0.25	0.34	0.34
Total run time (h)	6	6	1.37	12.5

Inorganic part	Fuel (%)	CG Replication 1 (%)	CG Replication 2 (%)	FBG Experiment 1 (%)	FBG Experiment 2 (%)
SiO <sub>2</sub>	73.24	71.30	71.25	73.71	96.28
Al <sub>2</sub> O <sub>3</sub>	7.92	8.92	8.96	6.20	0.86
CaO	3.69	4.16	4.13	2.49	0.46
Fe <sub>2</sub> O <sub>3</sub>	5.46	6.31	6.23	6.80	1.45
K <sub>2</sub> O	3.60	4.41	4.46	3.72	0.43
MgO	2.27	2.45	2.46	1.60	0.24
MnO <sub>2</sub>	1.31	0.15	0.15	0.69	0.03
Na <sub>2</sub> O	1.04	0.80	0.81	0.09	0.05
P <sub>2</sub> O <sub>5</sub>	0.84	0.92	0.96	0.63	0.10
TiO <sub>2</sub>	0.62	0.59	0.59	3.17	0.11

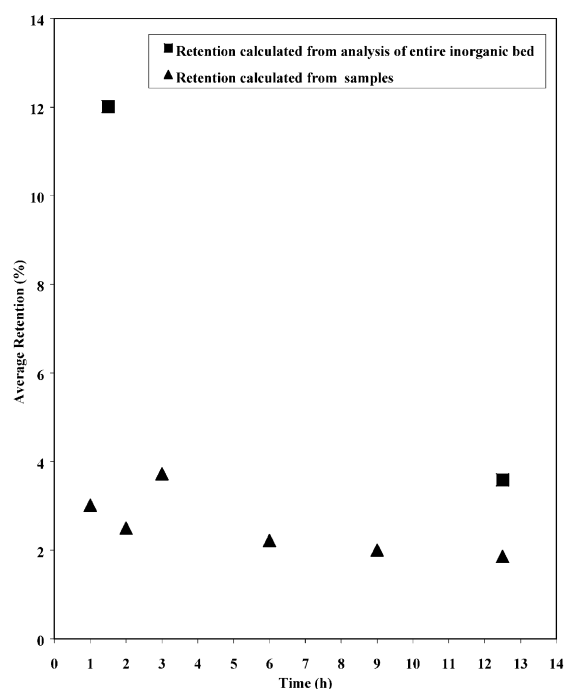


Fig. 4. Potassium retention in the bed as % of total potassium input with the fuel during the gasification test in the FBG.

The difference between the results from the two methods to determine the retention can be explained by in-homogeneities in the bed that lead to an underestimation of the K + Na contents if the local bed sampling results are used. It is likely that ash particles of

intermediate and coarse size are fluidised in the lean or dispersed phase<sup>2</sup> above the dense part of the bed. These particles have a considerably higher content of K + Na than the main bed. They will not be included in the bed samples but contribute to the K + Na content of the entire bed. It is possible to estimate the mass of ash particles that are fluidised above the bed. This would be about 16 g after 1.4 (h) and 21 g after 12.5 (h).

The bagasse gasification experiments in CG have shown that alkali separation is about 70% of the input alkali with the fuel at equivalence ratio of 0.25 and the amount of the char separated is 16% of the fuel input. Fig. 5 shows a comparison of the alkali separated with gasification residues in the CG and the total alkali average retention on the bed of the FBG. The alkali retention in the FBG was calculated from the analysis of the entire inorganic part of the bed.

The total alkali compounds contents of the producer gas and particulate entrained with the producer gas were calculated from the difference between input alkali with the fuel and the alkali separated/retention in

<sup>2</sup> The entrainment of the particles in an upward-flowing gas stream is a complex process. In general, fine particles entrain and leave the system and coarse and intermediate particles remain. This depends on the height of a freeboard. For a freeboard height less than the TDH (transport disengaging height), the size distribution of solids in the freeboard changes with position, with an increasing fraction of fine particles as the freeboard height approaches the TDH. At TDH, the entrainment becomes constant [9].

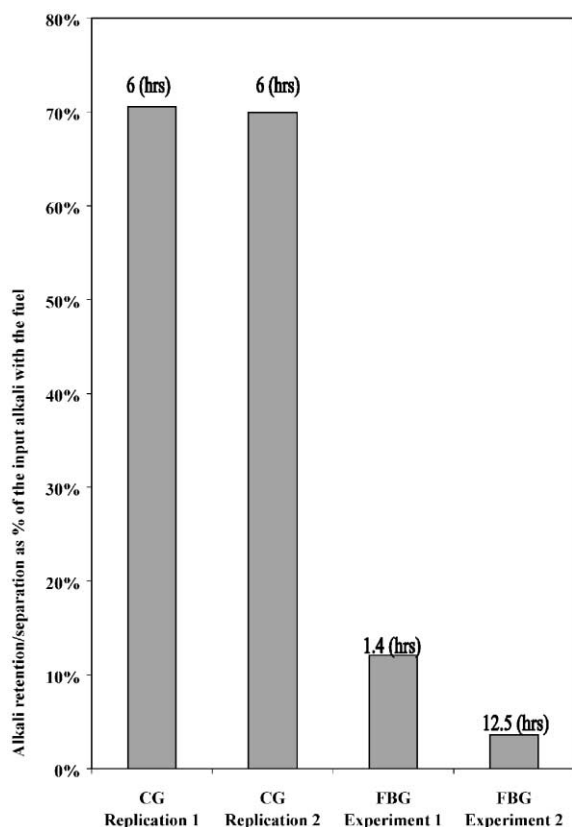


Fig. 5. Comparison of alkali retention/separated with char samples from bagasse gasification in FBG/CG.

the CG and FBG. In the CG, the total alkali compounds content in the producer gas and particulate in the gas were calculated to be about 155 mg/kg (wet-gas) and in experiments (1 and 2) of the FBG were calculated to be 265 and 285 mg/kg (wet-gas), respectively.

### 5.2. SEM/EDS analysis of bed samples

The samples for the SEM/EDS analysis were mounted in epoxy, cut by a diamond saw and polished. The resulting cross-sections were carefully examined by SEM/EDS spot and elemental mapping methods. The results of sample seven collected during the second gasification experiment were chosen to be presented in this paper. This is because sample seven should be representative of steady state condition, approached as the operation is continued, and where the loss of alkali is equal to the input with

the fuel. Also, sample seven includes the coarse and intermediate size ash particles in the dispersed phase.

Fig. 6 illustrates the back scatter image and elemental maps of the gasification residue of sample seven. The top figure is a back-scattered image of a number of bed particles. The dark area in the image is the epoxy resin in which the sample was mounted and the lighter areas are the cross-sectioned bed particles. The bottom figure shows results of elemental mapping analysis.

The extensive coating formation on quartz bed material particles that has typically been reported from combustion conditions [10] and some recent unpublished work for FBG could not be observed in the present work.

Coating is inorganic species attached to bed material particles by chemical fixation or physical adsorption. If there had been a coating it would be distinguished on the bed particles as a lighter periphery surrounding the particles core, see, for instance [10]. None of the seven samples was found to contain any significant coating, and the ash was instead found in a presumably non-sticky ash matrix, separate from the bed particles consisting of mainly Si, Al and K, as can be observed in the bottom part of Fig. 6.

## 6. Theoretical studies

Chemical equilibrium model calculations were carried out to predict the form in which the alkali metals are released by the gasification of bagasse. It is of interest to know whether the compounds of sodium and potassium will be present in vapour phase or predominantly in condensed, liquid or solid form.

The theoretical distribution of sodium and potassium in the gasification product was calculated with equilibrium condition assumed. Gas mixtures are assumed to be ideal. The calculations were made using a computer program (Chemsage) developed by Eriksson [11]. This program, which uses the method of minimisation of the total Gibbs free energy of a system, has previously been used successfully in many similar studies. A large number of gaseous and solid species are included as well as state of the art solid and liquid solutions. Thermodynamic data were taken mainly from the data bank of the Scientific Group Thermochemical Data Europe (ESTE), used with the data for non-ideal silicate/oxide and salt solutions [12,13].

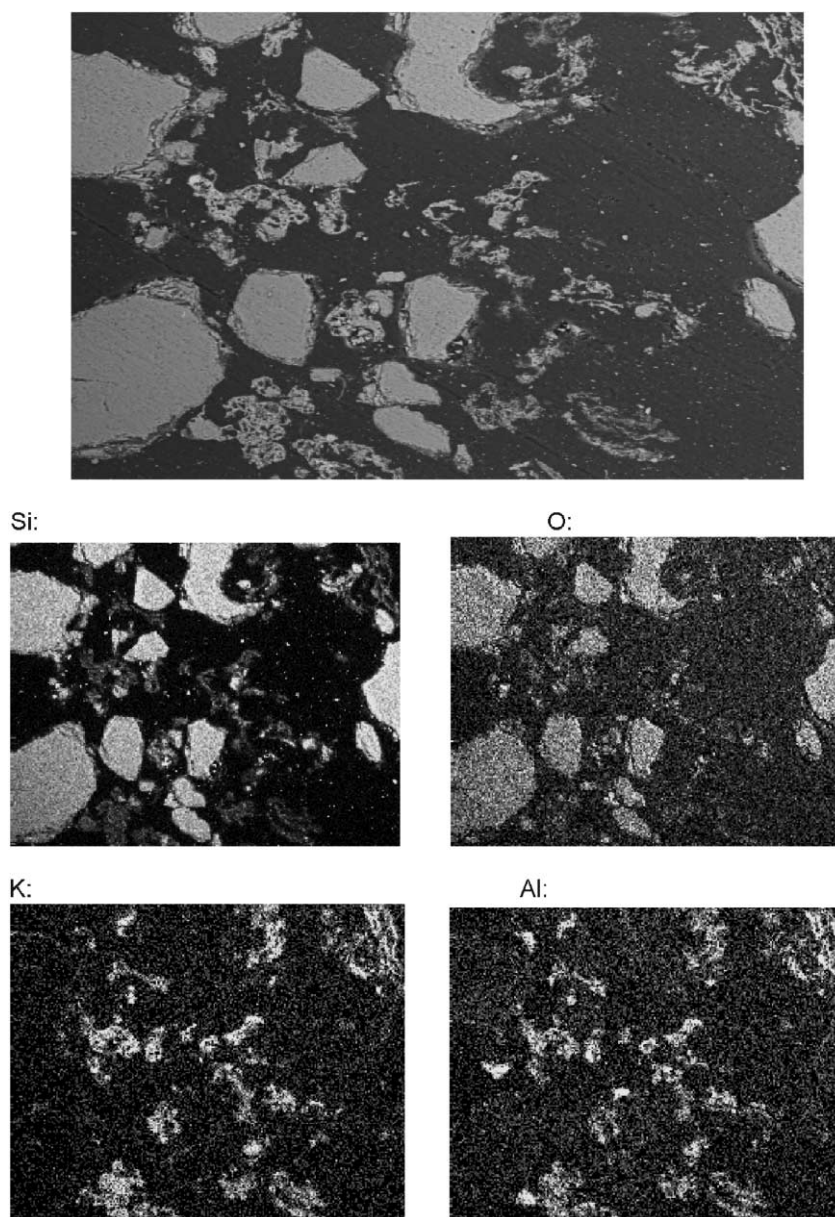


Fig. 6. Back scatter image and elemental maps of the bottom residue of the fluidised bed (sample 7), illustrating the K and Al rich silicate ash particles.

The equilibrium calculations were carried out covering a temperature ranging from 500°C to 1200°C, and equivalence ratios in the range of 0.15–0.35. Based on kinetic considerations, the material in the fluidised bed was assumed to be inert.

The calculations showed that monochlorides (KCl-g and NaCl-g) and to lesser extent dichlorides (K<sub>2</sub>Cl<sub>2</sub>-g and Na<sub>2</sub>Cl<sub>2</sub>-g) are the dominant alkali gas species under gasification conditions with equilibrium condition assumed. Elemental Na, K and the

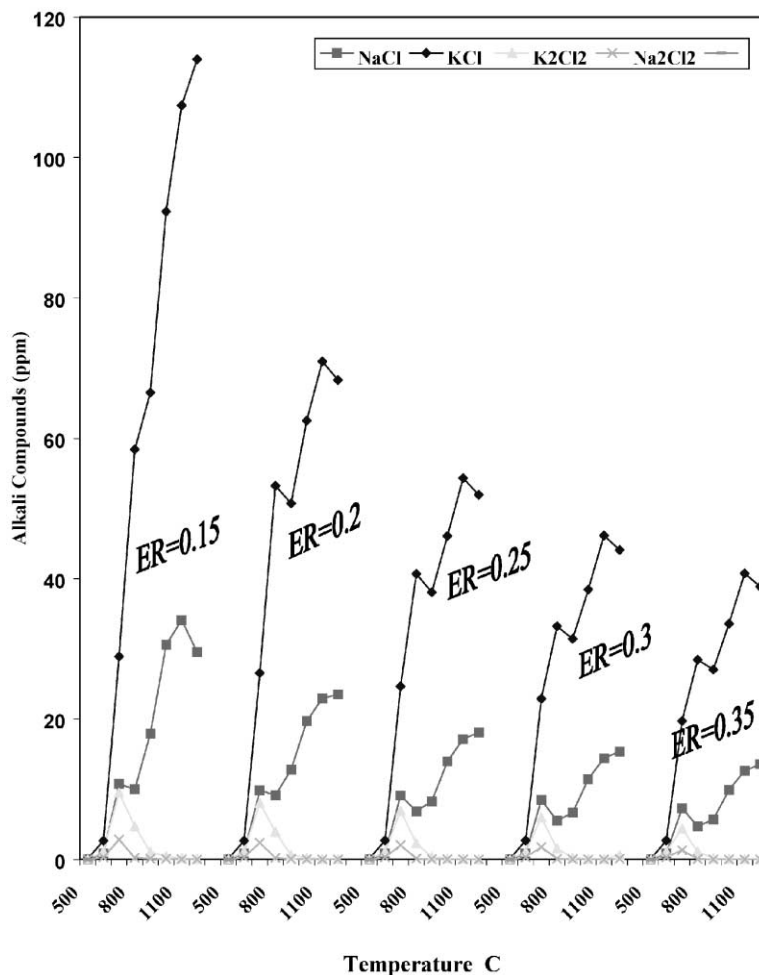


Fig. 7. Variation of gaseous species in the producer gas from gasification of bagasse with temperature and equivalence ratios.

hydroxides (KOH-g and NaOH-g) are also formed, but by almost an order of magnitude less than monochlorides and dichlorides. The elemental form of Na and K appear at higher temperatures (above 1000°C) in small quantities and their amount increase as the temperature is increased. The general trend is that the gas alkali phase in a producer gas from the gasification of bagasse at equilibrium conditions is increasing as the temperature is increased or as the equivalence ratio is decreased, see (Fig. 7).

The bagasse equilibrium calculations show that alkali is found in a solid phase at low temperature between 500°C and 600°C and most of alkali stayed in

liquid phase at the gasifier operation temperature of 800–900°C see (Fig. 8). The highest amount of liquid alkali phase appears between 800°C and 900°C and it decreases in favour of gas phase as the temperature is increased.

In the range of the equivalence ratios that were covered by the experiments, the effects of the equivalence ratios on the distribution between phases are marginal as shown in Fig. 8. However, the equilibrium calculations made for a wider range of the equivalence ratios show that the liquid alkali phase is increasing as equivalence ratios are increased whereas the gas phase alkali is decreasing.

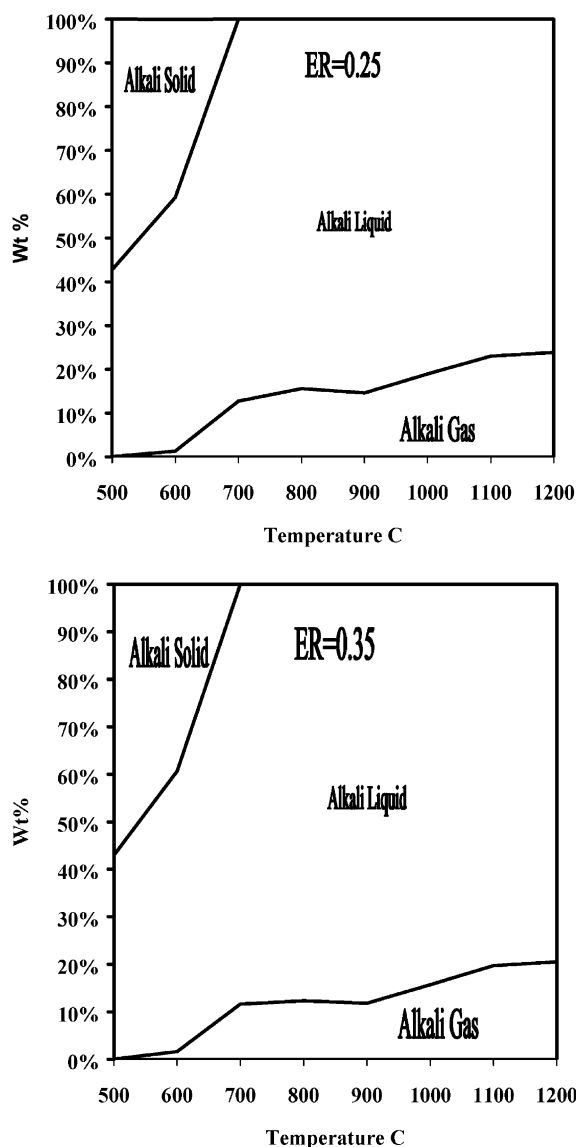


Fig. 8. Bagasse gasification—variation of alkali phase with temperature at 1 bar.

Fig. 9 gives indication that increasing the pressure has a significant effect on reducing the gas phase alkali content of the producer gas.

## 7. Discussion

The comparison between the observations for separation and retention of K and Na when the same type

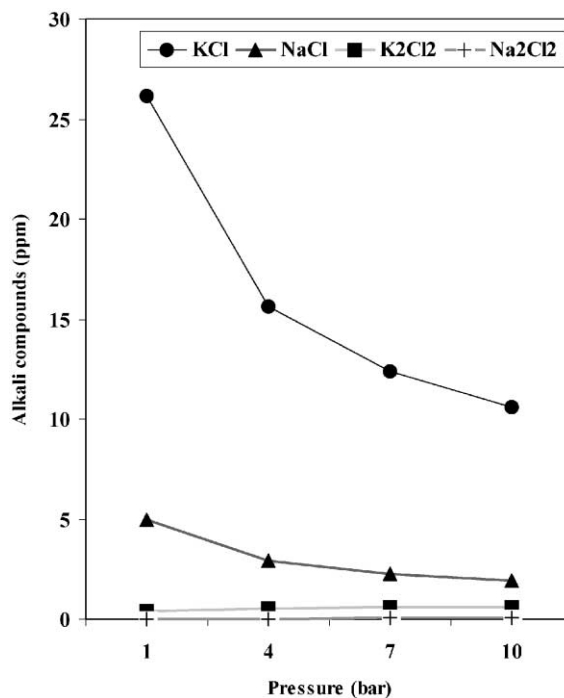


Fig. 9. Bagasse gasification—variation of the gaseous species with pressure.

of bagasse was gasified at 850°C in a cyclone and a fluidised bed shows clearly that the carry-over of K and Na to the product gas is considerably less when the cyclone gasifier is used, see Table 3. About 70% separation was observed for the cyclone gasifier, whereas the fluidised bed gasifier showed on an average 12% retention after 1.4 h of operation which dropped to 4% when the time of operation was increased to 12.5 h, see (Fig. 5).

The difference in performance can easily be explained. In the cyclone gasifier, char is continuously separated and removed. The ash included in this char carries significant amounts of K and Na which are not going with the product gas flow. In the fluidised bed gasifier, no solid material was removed from the bed except the particles entrained in the product gas flow. Accumulation of ash particles in the dense and lean phases of the bed and formation of coating on the sand particles in the bed are therefore the only mechanisms for retention of K and Na. No coating on the sand particles could be observed, see Fig. 6. Some accumulation of ash particles in the bed did apparently occur.

However, small ash particles will be caught by the gas stream and carried away. It seems that the larger and intermediate particles that originally remain in the bed will gradually be gasified (by the reaction with  $\text{CO}_2$  and  $\text{H}_2\text{O}$ ). The char of these particles is losing mass by char gasification and erosion until the particles are small enough to be carried away by the gas stream. Therefore, the retention can be expected to drop as the operating time is increased. Fig. 4 illustrated that in the long run FBG gasification test the retention drops from about 3% after 1 (h) to about 2% after 12.5 (h). The drop in average retention when the experiment was extended indicates that there is an initial build-up of alkali in the bed. However, as the operation is continued a balance is approached where the loss of alkali is equal to the input with the fuel, see (Fig. 5).

The discrepancies found between average retentions calculated from samples taken during operation and samples taken after completion of the experiment (samples 6 and 7 in the long gasification test) can be explained by inhomogeneities in the bed. The ash particles will mainly be found in the freeboard during operation. When operation is stopped these particles will fall down and be a part of the stagnant bed, see Fig. 4.

The observations made for the cyclone gasifier are consistent with results reported by Fredriksson [3]. The retention of K and Na observed for the fluidised bed gasifier falls between the results reported by Turn et al. [4] for bagasse and by Mojtahedi et al. [5] for peat. Turn et al. [4] reported 40% retention for bagasse after about 4.5 h operation. Some of the retention appears to be in the form of a coating on the bed particles. Mojtahedi et al. [5] found no retention in the bed. It is likely that differences in free-board velocities and sizes of ash particles can explain part of the differences in the retention observed. Differences in ash composition and composition of bed particles may explain why coating was found by Turn et al. [4] and not in this study. The bagasse ash tested by Turn et al. [4] included about the same fraction of K but much more Al and less Si. Also, the fresh bed material used by Turn et al. [4] had an Al/Si ratio much higher than that used in this study.

There are obvious discrepancies between the observations from the experiments and the results from the equilibrium calculations. The latter predict that 10–15% of the K and Na will be in gas phase at the operating temperature of the gasifiers and that the remain-

der should be in liquid phase, see Fig. 8. However, no indications of melting could be observed in any of the gasifiers. The ash retained in the FBG was found in presumably non-sticky, freely moving separated from the sand particles of the bed, consisting mainly Si, Al and K, see Fig. 6. In the cyclone gasifier, the ash composition in the separated char particles was found to be close to that of the fuel ash, as illustrated in Table 4. This indicates that no significant gasification of ash elements occurred from the separated char, in any case not for K, that has a content higher in the char ash than in the fuel ash. Others [4,5] have also found that equilibrium calculations give considerable overestimations of the gas phase K and Na species formed during biomass gasification.

Several explanations for the discrepancies between equilibrium calculations and experimental observations are possible. In the CG, the reactions during the gasification process may not reach equilibrium conditions because of short residence time. The short residence time may therefore keep the alkali elements in a solid form and the volatilisation of these elements will not occur. In the FBG, the time should be sufficient to reach equilibrium. Still it seems that the K is efficiently captured and transported in a form that will not result in coating around the bed particles or formation of a melt. It can therefore be assumed that Si, Al and K selectively formed some kind of potassium aluminium silicate with a relatively high melting temperature, which is continuously scavenged and lost from the bed through elutriation.

Since an important application of bagasse gasification could be generation of pressurised fuel gas for a gas turbine, it is of interest to know if the retention of K and Na would be different at elevated pressure. This can of course only be answered by gasification experiments at higher pressure but the results of the equilibrium calculations indicate that less gas phase species will be formed, see Fig. 9. Consequently, the retention at elevated pressure should not be expected to be less than observed for the experiments at atmospheric pressure.

## 8. Conclusions

From the results presented in this paper, the following conclusions can be drawn:

- A cyclone gasifier that is operated to generate a producer gas and char residue at a gas temperature of about 850°C will achieve significant separation of the Na and K supplied with the fuel. For the bagasse tested in this study about 70% of the input was found separated together with the char.
- For fluidised bed gasification of the same bagasse at the same temperature in a bed operated without removal of bed material and ash, the average retention of Na and K was found to be considerably less and dropping from 12% to 4% when the time of operation was increased from 1.4 to 12.5 h.
- In the fluidised bed gasification tests made here, no coating was observed around the particles of the bed material. In this test, the retention in the FBG is mainly caused by the ash particles accumulated in the bed (dense phase and freeboard). All the ash is found in the bed as solid ash particles, separated from the sand particles, consisting mainly of Si, Al and Si.
- According to equilibrium calculations for the ash of the bagasse that was tested, 10–15% of the input alkali should be in gas phase and the remainder in liquid phase at the operating temperature of 850°C used in the experiments. However, no ash melting was observed in any of the two gasifiers that were tested. The observations from the cyclone gasifier also indicate that at least the alkali carried with the char particles that were separated in the cyclone was not gasified to a significant extent. This confirms conclusions drawn by others that equilibrium calculations overestimate the formation of gaseous and liquid phases of biomass ashes in gasifiers.
- The different results reported in the literature regarding alkali retention for fluidised bed gasification can be an effect of different free-board velocities, ash particle sizes and freeboard height. The ash composition and composition of the bed material can also influence the retention. Retention by formation of a coating on bed particles cannot be excluded even though this was not observed in this study. Short operating time will also give values for alkali retention that are higher than what will be achieved for extended operation.
- Determination of alkali retention in fluidised bed gasification by sampling of the bed during operation can give misleading results as a consequence of vertical inhomogeneities in the particle size distribution with ash particles mainly found in the upper parts of the bed.

bution with ash particles mainly found in the upper parts of the bed.

- The performance as regards alkali separation and retention can be expected to be better at elevated pressure than for the atmospheric pressure used in the gasification tests made in this study.

## Acknowledgements

The authors would like to express their sincere appreciation of the assistance of Energitekniskt Centrum in Piteå, Sweden (ETC), where the experiments were carried out. Thanks are due to Mr. R.C. Rampling, the factory manager (in 1995) of Kenan Sugar Company Limited Sudan (KSC) for his co-operation and assistance in providing the project with the bagasse and cane trash. Financial support from the Swedish International Development Co-operation Agency (Sida) is gratefully acknowledged.

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