

Article

Co-Fuelling of Peat with Meat and Bone Meal in a Pilot Scale Bubbling Bed Reactor

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Abstract: Co-combustion performance trials of Meat and Bone Meal (MBM) and peat were conducted using a bubbling fluidized bed (BFB) reactor. In the combustion performance trials the effects of the co-combustion of MBM and peat on flue gas emissions, bed fluidization, ash agglomeration tendency in the bed and the composition and quality of the ash were studied. MBM was mixed with peat at 6 levels between 15% and 100%. Emissions were predominantly below regulatory limits. CO concentrations in the flue gas only exceeded the 100 mg/m³ limit upon combustion of pure MBM. SO₂ emissions were found to be over the limit of 50 mg/m³, while in all trials NO_x emissions were below the limit of 300 mg/m³. The HCl content of the flue gases was found to vary near the limit of 30 mg/m³. VOCs however were within their limits. The problem of bed agglomeration was avoided when the bed temperature was about 850 °C and only 20% MBM was co-combusted. This study indicates that a pilot scale BFB reactor can, under optimum conditions, be operated within emission limits when MBM is used as a co-fuel with peat. This can provide a basis for further scale-up development work in industrial scale BFB applications.

Keywords: bubbling bed reactor; meat & bone meal; co-combustion; flue gas emissions; peat

1. Introduction

In Ireland there are currently limited disposal routes available for mammalian meat and bone meal (MBM). Over 100,000 tons of MBM is produced annually in Ireland [1] and while two installations in the state are licensed to co-incinerate MBM as replacement fuels for coal and peat, the majority of Irish MBM is exported for incineration or co-incineration in the UK or Germany [2]. MBM is stored in 18 stores throughout Ireland. At the end of 2004, 78,000 tonnes of MBM was in storage awaiting thermal destruction [3]. Nowadays, the Irish slaughter industry produces approximately 550,000 tonnes of raw animal by-products to be processed into MBM each year [4]. Between 2001 and 2003 a total of €145 million was spent on the rendering and disposal of MBM [4]. From seven rendering plants Ireland produces about 150,000 tonnes of MBM per annum of which approximately 45,000 tonnes is specified risk material (SRM). All MBM (including SRM) produced in Ireland is treated at 133 °C at 3 bar for 20 minutes.

The safe disposal of MBM is necessary to prevent transmission of disease, in particular transmissible spongiform encephalopathies such as bovine spongiform encephalopathy (BSE) [5]. The ideal disposal method would offer a safe, secure and environmentally acceptable solution and, if possible, an energy recovery component to offset the logistical and processing costs. Within the EU Waste Management Hierarchy, thermal disposal, especially incineration with energy recovery, is a desired and viable option often used in industrialized nations [6]. Given the current restrictions on re-use and recycling of MBM and concerns regarding the effectiveness of composting, incineration with energy recovery seems a viable alternative from within the hierarchy [7]. The combustion of organic materials, such as peat, results in the production of significant amounts of CO₂. Replacing a portion of this material with less carbon rich non-fossil fuels will help to reduce emissions of CO₂, an important factor in view of the Kyoto protocol which calls for the reduction of green house gases.

McDonnell *et al.* [8] suggested several thermal disposal and disintegration methods for animal by-products. Indeed a number of studies have studied the potential of MBM to be used as a secondary fuel with coal [9–11]. In a study where low grade Greek brown coal and MBM blends (MBM:coal, 9:1, 4:1, 2.3:1, 1:1) were used, MBM was found to enhance pyrolysis although problems could arise by the high contents of phosphorous, calcium and chloride in MBM [10]. Senneca [9] found that when a full scale boiler was used to co-fire Colombian coal and MBM at a ratio of 16:1 large quantities of fine spherically shaped particles were produced with carbon contents of around 10% (w/w).

McDonnell *et al.* [8] has examined the use and performance of MBM as a co-fuel with milled peat in fluidized bed combustion installations (FBC). A series of combustion trials were conducted with an FBC (internal diameter of 10 and 30 cm) at the University of Twente, the Netherlands. Pellets (4.8 and 10 mm in diameter and approximately 10–15 mm in length) were made from a mixture of MBM and milled peat, at MBM inclusion rates of 0%, 30%, 50%, 70% and 100%. These pellets had a weight of about 0.3 g and contained 0%, 25%, 35%, 50% and 100% MBM inclusion with the peat. While research has shown that MBM can be successfully used as a co-fuel with peat, little further research has been done. The main advantage of FBC is the possibility of utilizing a wide range of fuels with varying physical and chemical characteristics, since proper mixing of fuels and bed material is secured. FBC is capable of converting fuels completely at lower temperature levels (750–900 °C) compared to

conventional combustion systems, while it offers the possibility to use bed material additives to reduce emissions levels.

Bubbling fluidized bed combustion (BFBC) technology is a modern combustion technology especially suitable for unhomogeneous bio-fuels [12]. BFBC installations have the advantage of being able to operate with higher residence times with lower fluidization velocity [13]. Kouvo and Backman [14] found that two main characteristics of BFBC that affect the release of trace elements and distinguish it from pulverized combustion are the combustion temperature and the interaction between the fuel and fuel ash and the bed material. In a BFBC technology, Basu [15] found that the circulation of fly ash from the cyclone improves the sulfur capture efficiency. Cummins *et al.* [16] studied the effects of the co-combustion of MBM and peat on flue gas emissions and fluidization when using a BFBC. It was concluded that the potential is good for using MBM as a co-fuel with peat in a BFBC while maintaining high air quality standards. In addition, it has been shown that combustion of MBM can be conducted with negligible societal risks [17]. In order to take the advantage of higher residence times with lower fluidization velocity and improve on accuracy of assessment of flue gas emissions and quality of the ash an experiment was developed with the following objectives:

1. To evaluate the suitability of MBM for co-combustion with peat in BFB combustor under various MBM / peat mixes, ranging from 15% to 100% MBM;
2. To study the effects of the co-combustion of MBM and peat on flue gas emissions, bed fluidization, ash agglomeration tendency in the bed, and the composition and quality of the ash.

2. Materials and Methods

2.1. Fluidized bed trial facility

MBM and peat co-combustion experiments were carried out with VTT Energy's (Jyvaskyla, Finland) fluidized bed trial facility of 20 kW output (Figure 1). The reactor consists of an air/water-cooled fluidized-bed refractory lining (ceramic) combustor. The top of the reactor is made of uncooled, thermally insulated acid-proof steel having refractory lining inside the walls. The desired temperature levels in the reactor were maintained with four separately controlled heaters at bed and freeboard areas. The bed area and two separate zones of the freeboard were cooled down with air or water if necessary. The sampling ducts and the cyclone for fly ash separation from the flue-gases were located in a horizontal pipe after the reactor. Cyclone and filter ash were collected and used as samples for further analysis.

Combustion air was preheated and separated the right proportion to primary, secondary and tertiary air. The amount of these were adjusted and measured by thermal mass-flow meters. The fuels were fed into the fluidized bed using two screw-feeders. Hot air (700 °C) was used to start the reactor before fuel feeding to heat the appropriate amount of sand to 650 °C. Silica sand was used as the bed material. The total amount of the bed sand varied between 1.6 and 1.8 kg depending on the fuel. The starting period of the reactor was about 2 hours.

Table 1. Experimental design showing combustion trial conditions.

Trials	Peat (wt% dry)	MBM (wt% dry)	T, °C (planned)	T, °C (performed)
1	85	15	880	877
2	80	20	880	881
3	80	20	820	818
4	65	35	880	881
5	66	34	820	824
6	0	100	820	831

Table 2. Fuel Properties and sulphur content analysis of peat and MBM material.

Parameters	Peat	MBM
Moisture content, w%	36.8	8.09
Ash content, w% (815 °C)	3.40	23.8
Volatile matters, w%	61.1	68.1
Calorific heating value (kJ/kg)	22560	19325
Net calorific heating value in dry matter, kJ/kg	21403	18192
Sulphur (S) content in dry matter, w%	0.28	

2.3. Flue gas and ash sampling procedure

Gas sampling schedule and combustion conditions during sampling are given in Table 3. Main flue gas analyses were carried out using a combination of traditional on-line analyzers and FTIR spectrometry. During each trial flue gas was sampled by suction pump, equipped with a gas meter, for analysis of HCl, VOC and Amino Acids.

Table 3. Gas sampling schedule and combustion conditions during sampling.

Trials	Parameters	Combustion conditions					
		CO (ppm)	NO (ppm)	O₂%	SO₂ (ppm)	CO₂%	Temp (°C)
1	HCl	7	84	5.9	44	14.5	118
	VOCs	10	91	6.1	36	14.3	118
	Amino acids	11	84	6.0	35	14.3	119
2	HCl + VOCs	17	77	5.9	57	14.2	119
	Amino acids	19	79	6.1	52	14.0	119
3	HCl	20	56	5.8	35	14.4	119
	VOCs	26	56	5.7	36	14.5	119
	Amino acids	21	55	6.2	31	14.0	119
4	Amino acids	59	60	5.9	77	14.2	119
	HCl	51	62	5.9	81	14.0	119
	VOCs	12	72	6.2	76	14.4	119
5	HCl	51	39	5.7	51	14.2	119
	VOCs	102	39	5.7	56	14.3	119
	Amino acids	43	37	5.8	49	14.1	119
6	HCl	227	25	6.5	142	12.0	119
	VOCs	188	25	6.4	128	12.0	119
	Amino acids	186	24	6.4	133	12.0	119

During trial 4, a flue gas sample was also captured for the analysis of polychlorinated biphenyls (PCB), chlorobenzenes and chlorophenols, polychlorinated dibenzo-p-dioxins (PCDD) and -furans (PCDF), and also for polycyclic aromatic hydrocarbons (PAH). Ash samples were taken from the ash separation cyclone (cyclone ash), from the bag house filter (dust collector ash) and from the bed (bed ash) for compositional analysis, and for estimation of the safety of the ash disposal by using so called leaching trial.

2.4. Flue analysis

Oxygen, carbon dioxide, carbon monoxide, sulphur dioxide, and nitrogen oxides were measured using Magnos 6 G, Uras 10 P, Uras 10 E, Radas 2 G and Radas 2 G analysers respectively from Hartman & Braun (Germany). Hydrocarbons were measured using FTIR spectrometry (Bomem MB-100, Canada). Temperature was recorded using a NiCr-Ni thermoelement. These devices all operated continuously and the readings were recorded every tenth second.

Volatile organic components (VOC_s) were determined partly by FTIR and partly by TENAX-sampling system, where the flue gas was sucked through a TENAX-tube. The concentrations of VOC_s (mg/N m³) were analyzed by purge-trap technique followed by GC/MS (P&T/GC-MS) using external standard. When the emissions of VOC_s (mg/N m³) are calculated the laboratory blank Tenax sample was used as a zero sample and the VOC_s values of it were subtracted from the measured samples.

The concentration of HCl (mg/N m³) in the flue gases were analyzed on-line by FTIR during Trial 1 and by titrimetric analysis after sampling during all of the trials. HCl must be measured from wet gas however water disturbs FTIR measurements of other gases. Hence HCl was analyzed during Trials 2–6 using only the titrimetric method.

The amino acids concentrations were analyzed by liquid chromatography after acid hydrolysis as detailed in Buck and Krummen [18]. The analyzed amino acids are asparagic acid, threonine, serine, glutaminic acid, glycine, alanine, valine, isoleusine, leusine, tyrosine, phelynealanine, histidine, lysine and arginine.

In order to determine the concentration of particulates in the flue gas (mg/N m³) the FBC-reactor was equipped with a bag house filter located after the cyclone. The mass (g) of the cyclone and filter ashes was measured after each trial run. The concentration of the particulates in the flue gas during each trial was then calculated using the flue gas flow rate (m³/s) and the duration of the trial (s).

The analysis of all organic compounds in the flue gas samples and amino acids analysis were carried out at VTT Chemical Technology (Espoo, Finland) and VTT Biotechnology and Food Research (Espoo, Finland) respectively.

2.5. Ash analysis

The concentrations of important elements in fuel mixture, cyclone and filter ashes and in some bed ashes (including carbon) were analyzed by XRF-analysis method at VTT Chemical Technology (Outokumpu, Finland).

The Toxicity Characteristic Leaching Procedure (TCLP) was carried out to determine the mobility of analytes present in the ashes, *i.e.*, in order to estimate the risk of loss of elements to the ground water. The procedure was carried out according to the standard TCLP method 1311 [19]. TCLP trials were

conducted for cyclone ash, dust collector ash and bed material samples. From colatures the mercury of the samples has been determined by PSA-analyzer cold vapour method and phosphorus (P) has been analyzed according to Finnish standard SFS 3026 [20]. Other metals have been determined using a Perkin-Elmer SIMAA 6000 graphite furnace atomic absorption spectrophotometer (Perkin-Elmer, USA).

The metal analyses of leaching trials were carried out at VTT Energy with the XRF-analysis of fuels and ashes completed at VTT Chemical Technology (Outokumpu, Finland).

3. Results and Discussion

3.1. Combustion conditions

Average combustion conditions; reactor temperatures, air amounts, the normalized flue gas composition and residence time for each trial are given in the Table 4. Fluidization airflow was 96 l/min, secondary was 96 l/min and tertiary was 41 l/min, therefore the total residence time in hot combustion conditions was 9 seconds. In general a linear relationship was observed between CO content and proportion of MBM in the fuel ($R^2 = 0.993$). However CO content was quite low, predominately in the range of 10 to 60 ppm. This was with the exception of trial 6 where pure MBM was combusted. The relationship between increased CO emissions with an increase in proportion of MBM in the fuel has also been observed during co-firing of coal and MBM [11]. The higher CO content (189 ppm) observed for trial 6 may be due to the higher volatile content of the pure MBM fuel and to the trend towards a lower freeboard temperature. Due to this NO content was minimized. Sulphur dioxide (SO₂) content was in the range of 30 to 80 ppm during co-combustion. In the last treatment, SO₂ content was higher because of the local reducing atmosphere where sulphates might decompose. In all of the trials conversion of sulphur to SO₂ was very low and the concentrations of NO_x in flue gases were also low when taking sulphur and nitrogen content of fuels into account.

Table 4. Average combustion conditions during the Trials.

Trial No.	Reactor temperature °C				Air amount (N l/min)			Flue gases				Residence time (s)
	Bed	FB1	FB2	FB3	Fluidization air	Secondary air	Tertiary air	CO ppm	NO ppm	O ₂ %	SO ₂ ppm	
1	871	889	882	867	96	96	41	11	84	6.02	35	8.8
2	882	890	882	869	96	96	41	19	78	6.08	51	9.1
3	813	840	821	797	96	96	41	21	55	5.97	32	9.6
4	891	887	881	864	95	95	42	59	60	5.92	77	8.9
5	819	846	825	805	95	95	42	40	38	5.70	51	9.4
6	851	846	819	808	95	95	42	189	24	6.42	134	9.0

3.2. Flue gas analysis

The average concentrations of flue gas compounds are given in Table 5 as calculated flue gas emissions (mg/N m³) in measured flue gas O₂ concentrations. Emissions were mainly below the limits stated in the IPC Guidance Note for combustion of MBM [21]. Although conversion of sulphur to SO₂ was low, SO₂ emissions were over the limit of 50 mg/m³. Concentrations of NO_x in flue gases were

also low when taking the high nitrogen content of the fuels into account. Indeed NO_x emissions were below the limit of 300 mg/m³ in every trial.

The VOC_s results of TENAX-sampling are given in Table 6. VOCs contents were clearly below the limit of 20 mg/m³. Gulyurtlu *et al.* [22] found that it was also possible to co-combust MBM and coal with a minimum impact on VOC emissions. It has also been shown that although at very low levels VOC emission are higher when 100% MBM is combusted rather than a MBM-coal mixture [23].

Table 5. Flue gas emissions (mg/N m³) and O₂ contents (%).

Trials	CO	NO	SO ₂	N ₂ O*	NO*	NO ₂ *	Gas O ₂ %
1	14.35	112.24	101.21	0.47	120.59	2.92	6.02
2	24.00	104.44	146.4	6.90	100.74	2.45	6.08
3	26.56	73.77	91.33	21.18	76.05	0.16	5.98
4	73.67	80.95	220.84	n.m**	n.m**	n.m**	5.92
5	49.46	51.52	144.88	24.34	51.78	0.17	5.70
6	236.26	32.79	383.13	66.78	28.92	0.10	6.42

* FTIR spectrometer. ** n.m. = not measured.

Table 6. VOC, CO, CO₂ and Hydrocarbons content and concentration of VOC in flue gases.

Trials	FTIR (mg/N m ³)					TENAX
	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	CH ₄	C _x H _y (sum)	Hydrocarbons, Sum (µg/m ³ N)
1	6.78	12.07	0.85	0.00	19.7	13.62
2	4.46	1.55	0.00	0.01	6.02	43.49
3	4.26	4.21	0.00	0.01	8.48	117.5
4	0.05	0.08	0.00	0.96	1.09	17.07
5	3.65	1.44	0.00	0.18	5.27	53.5
6	17.67	6.91	0.08	17.26	41.92	17.27

Determination of polychlorinated biphenyls (PCB), chlorobenzenes and chlorophenols, polychlorinated dibenzo-p-dioxins (PCDD) and -furans (PCDF), and polycyclic aromatic hydrocarbons (PAH) of the flue gas sample from trial 4 were conducted. Average flue gas composition and flue gas temperature during the sampling of the organic compounds were: CO (58.6 ppm), NO (60.5 ppm), O₂ (5.9%), SO₂ (77.0 ppm) and T (119 °C).

The content of PCB compounds, polychlorinated dibenzo-p-dioxins and -furans (PCDD and PCDF), chlorobenzenes, polycyclic aromatic hydrocarbons (PAH), are presented in Table 7. Analyzed dioxins (PCDD/PCDF) concentration of flue gas was 0.41 ng/m³ N, and its limit is 1 ng/m³. The concentrations of other analyzed hydrocarbonates were also low.

It has previously been reported that the substitution of coal with MBM may increase PCDD and PCDF production [23]. The suggested mechanisms for this effect included the inhibitive effect of SO₂ on chlorine activity which prevents PCDD/F formation and the increase in the superficial area to catalyse reactions due to the decrease in the particle size of the particulate matter emitted due to increased levels of MBM [24]. Indeed for co-combustion trials in a BFB reactor chlorine content was clearly correlated with PCDD and PCDF level [25].

The mass of the cyclone and filter ashes was measured after each trial run and the results are presented in Table 8. In all cases the concentration of particulates was higher than the limit of 25 mg/m^3 [21]. However the effect of dust cyclones were not taken into account as their effect was not measured in the combustion trials. In a boiler or incinerator installation this particulate matter is composed, mainly, of fly-ash [16]. The use of cyclones and baghouse filters are well know to reduce particulate emissions [26,27].

Titrimetric analysis results for HCl are given in Table 9. The average HCl concentration measured by FTIR during Trial 1 was 26 mg/N m^3 . The HCl contents in the flue gases varied near the limit of 30 mg/m^3 . The combustion of 100% MBM resulted in the lowest HCl emission ($3.6 \text{ mg/m}^3 \text{ N}$). It has previously been demonstrated that the presence of HCl will promote SO_2 capture by bed material and fly ash particles [28].

Table 7. The PCB, PCDD and PCDF, Chlorobenzenes, Chlorophenols and PAH concentration in the sample and in the flue gas.

Compound (Sum)	Sample/Concentration $\mu\text{g/sample}$		Concentration, $\mu\text{g/m}^3 \text{ N}$	
	Blank	Trial 4	$\text{O}_2 = 5.9\%$	$\text{O}_2 = 11\%$
PCB	0.43	0.67	0.032	0.021
PCDD & PCDF	0.34	2080		0.00041
Chlorobenzenes			0.106	0.07
Chlorophenols			0.082	0.054
PAH	6.9	120	26.479	17.499

Table 8. The mass of the cyclone and filter ash after the trial run and concentration of particulates before the cyclone.

Parameters	Trial Number					
	1	2	3	4	5	6
Cyclone ash, g	37	48	60	42	81.6	92
Dust ash, g	10.7	4.29	6.2	2.04	1.3	4.03
Particulates in the flue gas, $\text{g/m}^3 \text{ N}$	0.70	0.79	0.99	0.93	1.46	5.35

Table 9. Analyzed HCl in measured O_2 concentration and reduced in 11% O_2 concentration.

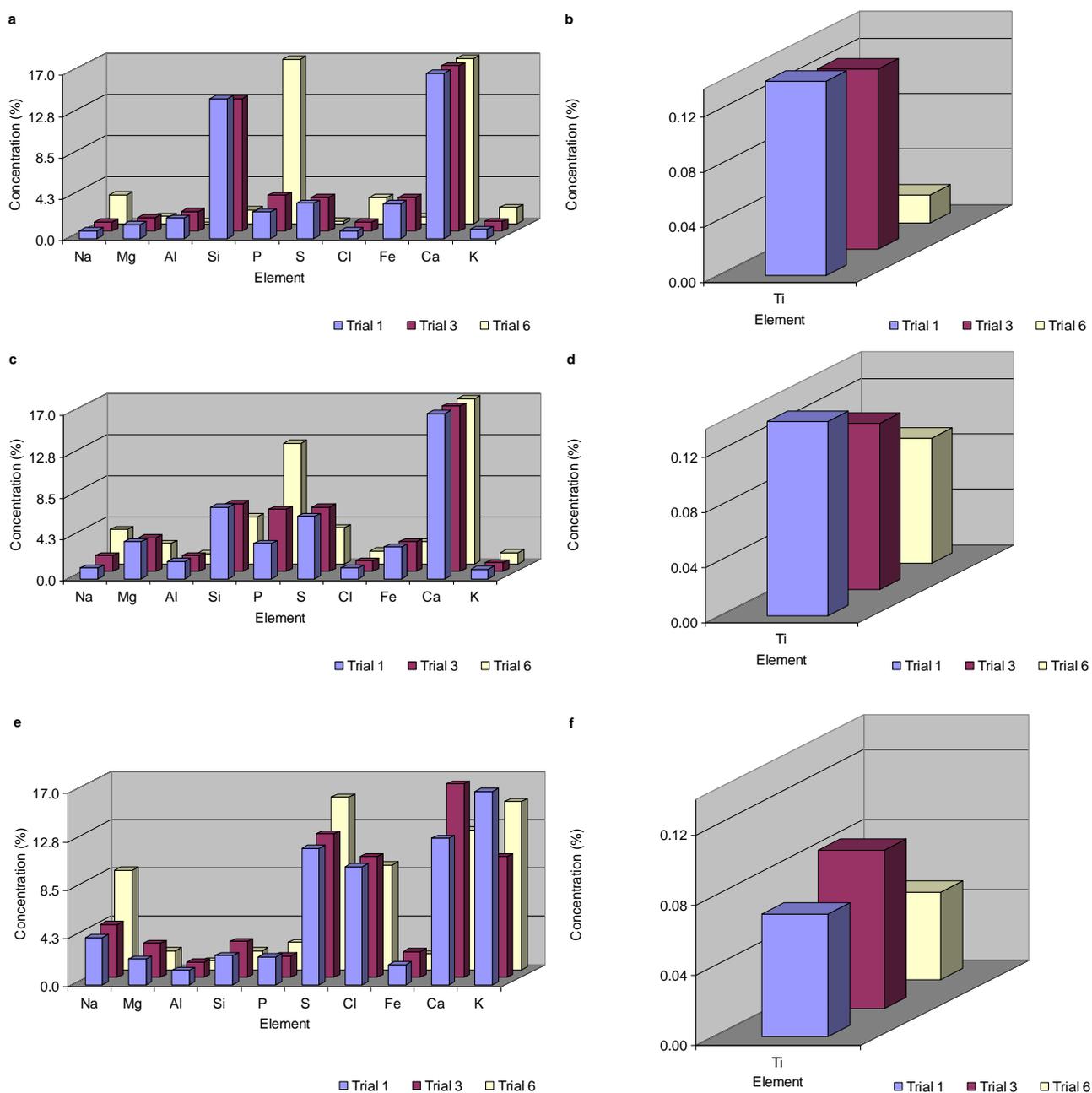
Trial	$\text{O}_2 \%$	HCl $\text{mg/m}^3 \text{ N}$	HCl ($\text{O}_2 = 11\%$) $\text{mg/m}^3 \text{ N}$
1	6.0	28.414	18.696
2	5.9	64.721	42.781
3	6.1	51.122	33.894
4	6.0	43.846	29.158
5	5.8	50.191	32.925
6	6.5	5.218	3.590

3.3. Ash analysis

The concentrations of the main elements, having an influence on the ash melting behaviors are presented in Figure 2 (results for the trials 2, 4 and 5 are not shown). The highest concentration of sodium (2.97%) in the fuel mixture ash occurred when pure MBM was combusted (trial 6). Sodium

concentrates to fine dust ashes of the filter more than to the cyclone ashes. The concentration of magnesium decreased as the proportion of the MBM fuel increased as peat contains more magnesium than MBM. The proportion of the magnesium is approximately the same in cyclone and dust ashes. The aluminum of the fuel mixture ash comes from the higher aluminum content of the peat. In trial 6 in which 100% MBM was combusted, the concentration of the aluminum is only 0.18%. Sodium concentrates equally to dust and cyclone ashes. The amount of the silicon is high in every fuel mixture ashes except in trial 6 in which pure MBM was combusted. Silicon concentrates mostly to the cyclone ashes.

Figure 2. Results of XRF analysis showing the concentration of the most important elements in the (a, b) fuel mixtures, (c, d) cyclone, and (e, f) dust separation ashes for trials 1, 3 and 6.



MBM ash contains a large amount of phosphorus as could be seen from trial 6 and it concentrates mainly to the cyclone ashes. Coarse bed ash particles have also high concentration of phosphorus. Sulphur capture into the ashes is relatively high in every performed trial which can be seen also as a low SO₂ conversion in the combustion calculations presented in Table 5. In particular the amount of sulphur in the fine filter ashes is very high. MBM ash contains a large amount of calcium and phosphorus, which could promote the binding of sulphur into the ashes, forming sulphates. The proportion of the chlorine is relatively high in MBM ash in trial 6.

Cl is captured to ash, especially to the dust filter ash, so the conversions in the flue gases are low (Table 9). Potassium content in fuel mixture ashes is almost the same in every trial. Potassium concentrates mostly to the dust ashes in combusting conditions and could also promote binding of sulphur and chlorine. Calcium is the main element in fuel mixture ash and it concentrates more to the cyclone ash than dust ash in combusting conditions. It is also an important element concerning the sulphur capture into the ash. It has been demonstrated previously that when HCl is present in the combustor that the utilization of calcium for SO_x capture is improved [28]. Calcium occurs also in the form of phosphate. MBM ash does not contain significant quantities of titanium. The amount of titanium in the fuel mixture ashes consists of titanium from the peat. Titanium concentrates more into the cyclone ash than dust filter ash. The iron content in the fuel mixture ashes decreases as the share of the MBM increases. Iron seems to concentrate into the coarse cyclone ashes. The composition of ashes from co-combustion of peat and MBM seems to be much more complicated than compositions of ashes from peat or bio-fuels fired boilers. The concentrations of chlorine, sulphur and phosphorous in fine ashes are exceptional high. Simultaneously ashes contain a great amount of calcium and potassium, which can bind chlorine and sulphur in solid form and reduce the flue gas emissions.

The concentration of amino acids in cyclone and filter ash samples and also in flue gas samples was found to be under the determination limit of the analysis method. This indicated that the prion protein would not survive the combustion processes.

3.4. Leaching behavior of the ashes

The concentrations of elements released from the ashes, into the water (100 g of ash and 1 liters of water) are shown in Table 10. For the 100% MBM, it is noticeable that As and P increased dramatically. All other results remained relatively constant. All samples studied had TCLP leachate concentrations for the elements studied below advisable limits[19]. Skodras *et al.*[29] examined the leaching and toxicity behavior of ashes resulting from the co-combustion of coal and MBM. They also found that none of the cyclone fly ash samples exceeded the maximum EPA limits hence they stated that they are acceptable for safe disposal. However they did find that increasing the amount of MBM in the fuel blend increased the toxic effect of the ash leachates on *Vibrio Fischeri*.

In general increasing the proportion of MBM in the MBM-peat blend increased the concentration of As, P and Ni in the leachate from cyclone ash. This was in contrast to the results of Skodras *et al.* [29] where decreasing the proportion of MBM in MBM-coal blends increased As and Ni. However similar to [29] Cr was found to decrease when the proportion of MBM increased.

Table 10. Content of analyzed elements released from the cyclone ash, dust collector ash and bed material, μg in 1 liter water.

Trials	Cyclone ash								
	As	Pb	Cd	Cr	Cu	P	Zn	Ni	Hg
1	12.0	271	0.5	500	4.40	140	50	153	0.124
2	23.8	482	1.7	320	80.0	160	102.5	150	0.01
3	12.3	189	0.5	189	4.70	94	50	141	0.01
4	39.6	198	0.5	165	1.30	240	50	152	0.01
5	71.3	206	0.5	111	14.8	560	50	186	0.01
6	188	181	0.5	90.0	7.10	700	70	211	0.01
Dust collector									
1	707	322	23.0	990	190	2200	440	1810	0.567
3	164	248	7.70	370	70.0	300	200	200	
Bed material									
5-coarse	8.80	2.0	0.70	2.0	13.7	260000	490	19.4	
5-fine	22.6	2.0	0.50	2.0	4.70	210	220	28.2	0.01
6-coarse	5.40	2.0	0.50	2.0	13.1	260000	350	21.3	0.01
6-fine	5.80	2.0	0.50	2.0	3.20	74000	350	18.0	0.01
Limit									

4. Conclusions

CO content was quite low varying mainly in the range of 10 to 60 ppm, except for trial 6 when 100% MBM was combusted. Slightly higher CO content (189 ppm) may be due to higher volatile content of MBM and to the simultaneously lower freeboard temperature. Sulphur dioxide content was in the range of 30–80 ppm during co-combustion. In trial 6, SO_2 content is higher due to the local reducing atmosphere where sulphates might decompose.

Emissions were mainly below the limits stated in the IPC Guidance Note for combustion of MBM. In all trials conversion of sulphur to SO_2 was very low, but SO_2 emissions were over the limit of 50 mg/m^3 . Therefore in order for such a facility to operate an SO_2 abatement strategy must be introduced. The inclusion of a suitable sorbent such as limestone should reduce the SO_2 to below the limit required. Concentrations of NO_x in flue gases were also low when taking the high nitrogen content of the fuels into account. NO_x emissions were below the limit of 300 mg/m^3 in every trial. The HCl contents in the flue gases varied near the limit of 30 mg/m^3 and VOCs contents were clearly below the limit of 20 mg/m^3 . Amino acids were not found in any flue gas and ash samples. All the concentrations were below the determination limit of analysis method. Analyzed dioxins (PCDD/PCDF) concentration of flue gas was $0.41 \text{ ng/m}^3 \text{ N}$, and its limit is 1 ng/m^3 . The concentrations of other analyzed hydrocarbonates were also low.

During the trials bed agglomeration and ash melting occurred only once. This took place when the fuel mixture contained 35% of MBM and the combustion temperature was $880 \text{ }^\circ\text{C}$. The melting of ash caused bed agglomeration and fluidization ceased. The main reason for bed slagging was melting of calcium phosphate. Fluidization problems such as bed agglomeration and ash sintering can be avoided when bed temperature is about $850 \text{ }^\circ\text{C}$ and share of the MBM is not more than 20%. In conclusion the results of this study indicate that a BFB reactor can, under optimum conditions, be operated within emission limits when MBM is used as a co-fuel with peat.

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