Combustion characteristics of reed and its suitability as a boiler fuel

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SUMMARY

In recent years, common reed (*Phragmites australis*) has become a conservation problem in Estonia because it has spread into ecologically valuable habitats, out-competing other species and impacting on biodiversity values. Thus, the use of common reed as a biomass fuel may not only provide renewable energy, but also help in biodiversity conservation efforts. The properties of reed as a potential biofuel must be studied because the fuel handling method, the lifetime of combustion equipment (fouling, erosion and corrosion), combustion regimes and environmental impacts such as pollution, ash handling *etc*. depend on these properties. The combustion characteristics of reed vary to some extent depending both on the site where it grows (coastal area, lake, river delta or wetland treatment system) and seasonally (winter or summer harvesting). This paper presents the results of tests on reed properties including the chemical composition of summer and winter harvested reed and its ash, ash fusibility temperature, physical properties such as moisture and ash proportions, dry bulk density, calorific value and energy density. The impacts of different chemical and physical properties of reed on boiler operation are discussed.

KEY WORDS: common reed; chemical properties; physical properties; impact on boilers

INTRODUCTION

Common reed (*Phragmites australis* [Cav.], Figure 1) is one of the most widely distributed vascular plants in the world, occurring on all continents except Antarctica. It is one of the dominant plant species in European land–water ecotones (Ikonen & Hagelberg 2007). It thrives in the strongly moisture retentive soils of marshes and swamps and grows well on the shores of streams, lakes and ponds, as well as in shallow water, ditches and wet wastelands. It grows best in firm mineral clays and at water levels between -15 cm and +15 cm relative to the soil surface, tolerating moderate salinity and burning if the water level is above the soil surface. The soils where common reed grows are very varied, but it prefers nutrient-rich soils with organic matter content up to 97 %. Soil pH may range between 3.6 and 8.6. Common reed is capable of vigorous vegetative reproduction and typically forms dense, virtually monospecific stands (Ikonen & Hagelberg 2007).

The plants generally flower and set seed between July and October and may produce great quantities of seed, which is then dispersed. In some cases, however, most or all of the seed produced is not viable. Seeds are normally dispersed by wind but may also be transported by birds. Following seed setting, nutrients are translocated down into the rhizomes and the above-ground portions of the plant die back for the winter season (Santi 2007).

In recent decades, common reed has become a serious conservation problem in some areas as it has spread into ecologically valuable habitats, out-competing most other species resulting in a rapid decrease in species diversity. The main reasons for the expansion of the common reed are:

a) decreased management activities, mainly grazing and mowing;
b) comparatively mild winters without permanent ice to destroy reed rhizomes; and
c) increased mean ambient temperature, which favours the growth of reed (Ikonen & Hagelberg 2007).

While reed is currently rarely used as a fuel, it is important to know its characteristics and try to assess its impact on combustion equipment, which may be affected by moisture, ash proportion (content) and composition of mineral matter.

If reed is used as a fuel in wood-fired boilers, the significantly lower fuel density of reed (60 kg m^{-3}) compared to wood chips (250–300 kg m^{-3} at the same humidity) should be considered (Komulainen *et al*. 2008). Moreover, the ash content of reed is 3–4 times greater than that of wood chips. In the Nordic countries the water content of growing reed is lowest during March to May when new shoots have not yet grown and frost creates convenient conditions for mowing. The composition of reed ash depends on the time of harvest, with winter

Figure 1. Common reed. Above: stems with inflorescences; below: rhizomes.

harvested reed showing the highest ash (SiO_2) content. Alkali metal oxides melt with the silica, forming compounds, at a lower temperature (Link *et al*. 2012). The resulting reed ash volume is very high and the heap of ash does not collapse on the grate of a stoker burner as wood fuel ash does (Figure 2). (A stoker burner is an automatic solid biomass combustion device placed inside the furnace of the boiler. Stoker burners are of two types, known as ‘under-fed’ and ‘horizontally fed’.)

Ash as a solid residue of combustion plays an important role in the selection and running of combustion equipment and its auxiliary devices. The amount of ash and especially its physical and chemical properties determine the design of the combustion equipment, the processes in the gas phase, the operating mode, construction of the ash handling system, the effect on the surrounding environment, and so on.

Reed has been used to provide energy in various European countries such as Estonia, Finland, The Netherlands, Hungary and Romania. The properties of reed as an energy plant closely resemble those of reed canary grass (*Phalaris arundinacea*) (ECN undated) but, unlike that grass, common reed does not need to be fertilised.

Knowledge of the fuel properties of common reed is essential not only to the assessment of its effect on the combustion equipment, but also in assessing combustion regimes and the environmental impact of substituting reed for fossil fuels. In this paper we analyse the fuel properties of reed in relation to site characteristics and time of harvest (winter or summer) by measuring moisture proportion, calorific value, and ash proportion and composition (TTÜ 2008).

METHODS

We measured reed yield at 27 different sites (Table 1) in nine Estonian counties in both the winter–spring and the summer period of 2006–2007, mainly in February–March and July–August (Table 2). The aim of the investigation was to clarify the energy potential and the combustion characteristics of reed that grew in different places. Determination of the moisture content of harvested reed started as early as 2002 with samples collected annually at Rocca-al Mare Bay, Tallinn (Figure 3).

Figure 2. Reed ash in the grate of a stoker burner.

Table 1. Productivity and moisture content of Estonian reed. Samples were collected during February–April 2006 (precise dates of collection are given in the second column). ‘p’ = parish, ‘NP’ = National Park.

	County, town, parish, date	**Specific location**	**Wet mass density (t ha^{-1})**	**Dry mass density (t ha^{-1})**	**Moisture proportion (%)**
1	Põlvamaa, Värska parish (p.), 10.02.06	Popovitsa village (v.), Peipsi	10.8	8.5	21.4
2	Põlvamaa, Mikitamäe p., 10.02.06	Lüübnitsa v., Peipsi Lake	9.3	7.4	20.0
3	Tartumaa, Meeksi p., 10.02.06	Mehikoorma v., Peipsi	6.3	4.9	22.6
4	Harjumaa, Loksa p., 15.02.06	Turbuneeme v.	11.0	8.8	19.8
5	Harjumaa, Kuusalu p., 15.02.06	Tapurla v.	8.7	6.5	24.8
6	Saaremaa, Muhu p., 03.03.06	Linnuse v.	6.2	4.9	20.4
7	Saaremaa, Pöide p., 03.03.06	before Väinatamm,	7.8	6.1	21.0
8	Saaremaa, Laimjala p., 03.03.06	Ruhve v.	7.8	5.9	24.1
9	Hiiumaa, Käina p., 10.03.06	Vaemla (Laisna) v.	11.2	9.3	17.5
10	Hiiumaa, Orjaku study path, 10.03.	at lighthouse	8.8	7.3	18.0
11	Viljandimaa, Kolga-Jaani p., 13.02.2006	Vaibla v., Võrtsjärv	6.2	4.8	22.4
12	Viljandimaa, Rannu p., 13.02.2006	Jõesuu v., Võrtsjärv	5.0	3.8	24.6
13	Saaremaa, Kaarma p., 10.03. 06	Mullutu Bay	6.7	5.5	17.6
14	Saaremaa, Kaarma p., 10.03. 06	Suurlaht	3.0	2.5	17.1
15	Saaremaa, Kaarma p., 10.03. 06	Kasti Bay	4.3	3.6	17.2
16	Läänemaa, Matsalu NP , 18.03.06	Kirikuküla	7.1	6.0	15.3
17	Läänemaa, Matsalu NP, 18.03.06	Mouth of Tuudi River	8.5	7.3	14.8
18	Läänemaa, Matsalu NP, 18.03.07	Kirikuküla	1.9	1.6	14.9
19	Pärnumaa, Häädemeeste p., 24.03.06	Rannametsa v.	12.6	9.8	22.3
20	Pärnumaa, Tahkuranna p. 24.03.06	Tahku v.	7.1	5.8	18.4
21	Pärnu town, 24.03.06	Papiniidu street	6.3	5.2	18.5
22	Läänemaa, Noarootsi p., 17.03. 06	Sutlepa Sea	3.9	3.3	16.8
23	Läänemaa, Oru p., 17.03.2006	Saunja Bay	4.5	3.8	16.4
24	Tallinn, Rocca al Mare, 28.03.2006	Kopli Bay	13.8	7.4	46.5
25	Haapsalu town, 8.04.2006	Tagalaht	15.9	12.4	20.6
26	Läänemaa, Hanila p., 8.04.2006	Virtsu v., Puhtu-Laelatu	14.8	11.7	20.9
27	**Average productivity of Estonian reed beds, winter–spring 2006**		8.1	6.3	20.5

Table 2. Average yield of Estonian reed beds in 2006 and 2007.

Period of measurements	**Average wet reed fuel density yield, as received (t ha^{-1})**	**Average oven dry reed fuel density yield (t ha^{-1})**	**Average moisture proportion, by mass (%)**
Winter–Spring 2006	8.1	6.3	20.5
Summer 2006	20.0	8.6	57.7
Winter–Spring 2007	9.1	6.6	26.4

Figure 3. Reed bed at Rocca-al-Mare Bay.

In each site samples were collected from one-metre square plots by cutting all the above-ground reed. The number of plots harvested at each site ranged from three to six, depending on visual inspection of the reed. Three plots were cut if plant growth (stem height and diameter) was even, and more plots were used if it was not. Wet mass of the reed was determined on site using electronic scales. Length and diameter of the stems was measured, then they were cut by hand into lengths of approximately 20 cm, sealed into plastic bags and taken to the laboratory the same day for further tests. Three to six replicate samples were taken at each site and mixed.

Samples were analysed and characterised regarding their proximate composition using the standard methods of CEN/TS 14774-1 (2004), CEN/TS 14775 (2004) and CEN/TS 15148 (2005). Ultimate composition analysis was carried out using a Vario EL CHNOS Elementary analyser. Ash chemical analysis followed the standard methods of DIN 51729 (ECN undated) and ISO 334 (1992). The element content of winter reed ash was determined at ENAS Oy in Jyväskylä (Finland) according to the standard methods of SFS-EN ISO 11885 (2009) and SFS-EN ISO 15586 (2011). The calorific value of the reed, q_b (MJ kg^{-1}) was determined in a calorimetric bomb in the laboratory following the CEN/TS 14918 (2005) standard method. Gross and net calorific values (q_{gr} and q_{net}, respectively) were distinguished. Gross calorific value includes the latent heat of condensation of water vapour in the products of combustion. The technical specification for determination of the fusion characteristics of ash followed CEN/TS 15370-1 (2006). Ashing was performed at a temperature of 550 ºC. In the ash-melting test, cylindrical pellets of length and diameter 3 mm were heated steadily, causing the ash to follow the sequence shrinkage, deformation, formation of a fluid hemisphere, and flow. This sequence was observed under a high temperature microscope (MOD 2 Carl Zeiss) operated at temperatures of 200–1,500 ºC with a temperature increase in the furnace of 10 ºC min$^{-1.}$ Four temperature cut-offs were identified as follows: deformation temperature DT, shrinkage temperature ST, hemisphere temperature HT and flow temperature FT. The test atmosphere was oxidising.

RESULTS

Table 1 presents productivity as mass determined in the field (t ha^{-1}), and the dry mass, from which the moisture proportion may be calculated. The values in the Table show the average productivity of reed on different sites in Estonia. Samples were taken in the period February–April.

The three sites with the highest productivities of dry matter were in Rannametsa Village, Häädemeeste Parish (9.8 t ha^{-1}), near the Orjaku dam on Kassari Island (9.3 t ha^{-1}), and in Haapsalu town (12.4 t ha^{-1}). The two smallest productivities were in a sedge-reed bed in Matsalu (1.6 t ha^{-1}) and in Suurlaht, Kaarma parish (2.5 t ha^{-1}). Overall, average dry mass productivity was 6.3 t ha^{-1} (wet mass 8.1 t ha^{-1}) in winter and 8.6 t ha^{-1} (wet mass 20.0 t ha^{-1}) in summer (Table 2, summer 2006).The two-year average reed dry matter yield in the winter–spring period was 6.5 t ha^{-1}. Figure 4 presents moisture content of common reed fuel samples collected in the same place in Rocca-al Mare Bay between October and May (winter harvest) in the years 2002 through 2006.

Calorific value

Winter and summer reed calorific values and energy density E_{20} (at 20 % moisture) are given in Table 3.

Elemental composition

Table 4 shows the elemental proportion of dry mass in fuel reed.

Ash content and composition

Table 5 shows that the proportion of chemicals in ash differs between winter and summer harvested reed and between soil types and fertilisation, with the largest differences being found in SiO_2 and K_2O. Different reed samples also show differences in other ash elements (e.g. Ca, Mg, Na, Al, Mn, P, S, Cl) (see Paist *et al*. 2007).

The ash proportion of reed harvested in winter is 2.1–4.4 %, (average 3.2 %), but for summer harvested reed it is significantly larger at 4.1–6.2 % (average 5.4 %). Data on the chemical composition of reed ash are shown in Table 5 and Figure 5, while Figure 6 shows differences in the proportions of some components of reed ash between seasons.

The chemical composition of reed ash for summer and winter harvests differs significantly in SiO_2 and K_2O. Quantities of the other chemical components of ash are all below 10 %.

The mineral composition of reed depends mainly on the type of soil where it grows and on the concentration of solutes in the water. The studies reported in this article did not include measurements of the concentration of solutes in the soil and water of harvested reed beds and, thus, the impact of prevailing conditions on the chemical composition of reed cannot be determined more precisely. In the boilers where reed fuels are intended to be burnt, the high variability of the content of inorganic components should be taken into account.

Ash-fusibility (melting) temperatures

Table 6 gives the summer and winter ash-fusibility temperatures of some samples of reed.

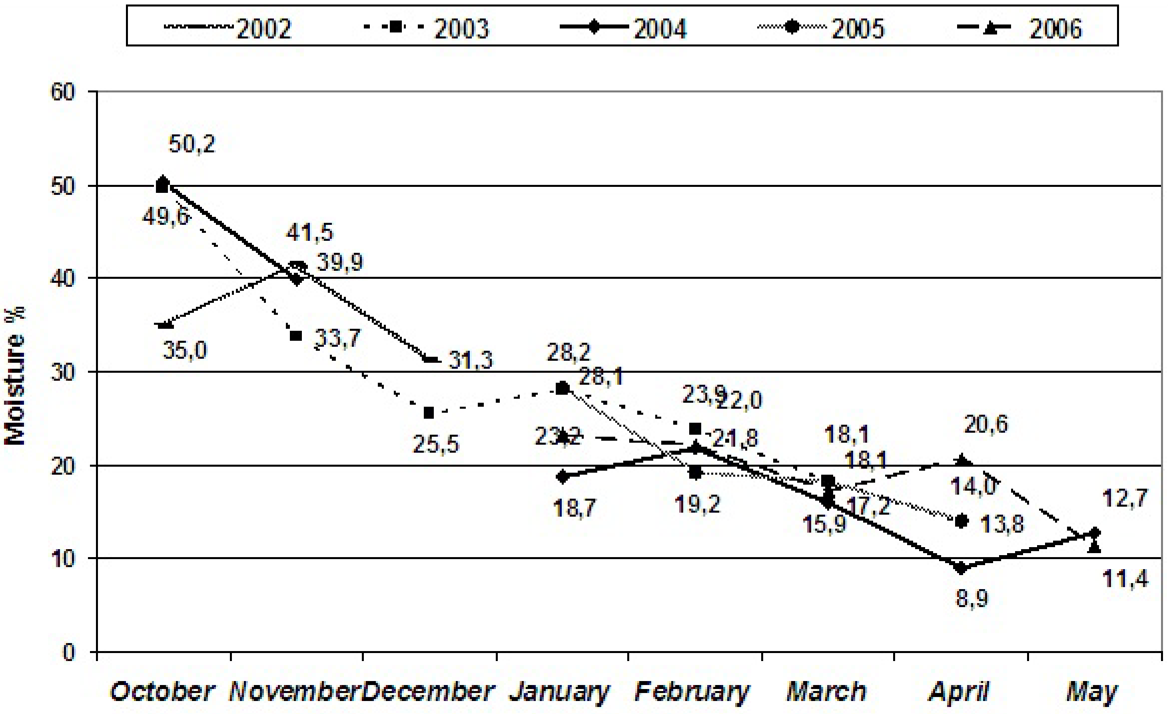

Figure 4. Moisture proportion of reed harvested between October and May (2002–2006).

Table 3. Calorific value of oven dry fuel reed, MJ kg^{-1}.

Parameters	Range		Average	
	Winter	Summer	Winter	Summer
$q_{b,}$ MJ kg^{-1}	18.6–19.2	18.3–18.8	18.9	18.5
$q_{gr,\,d,}$ MJ kg^{-1}	18.6–19.2	18.3–18.8	18.9	18.5
$q_{net,\,d,}$ MJ kg^{-1}	17.5–18.0	17.0–17.4	17.8	17.2
$q_{net,\,20}$ *, MJ kg^{-1}	13.7–14.9	13.16–13.5	14.2	13.3
E_{20}, MWh t^{-1} *	3.8–4.1	3.7–3.8	3.9	3.7

* E_{20} = energy density at 20 % moisture proportion (content).

Table 4. Elemental mass proportion of oven dry (at 105 °C) fuel reed, %.

Element	Range		Average	
	Winter	Summer	Winter	Summer
C	47.0–48.3	46.1–47.1	47.5	46.5
H	5.5–5.6	5.9–6.4	5.6	6.2
O	42.8–43.8	39.7–42.2	43.3	40.7
N	0.2–0.3	0.6–1.2	0.3	1.0
S	0.03–0.09	0.12–0.45	0.04	0.2
Cl	0.05–0.18	0.28–0.48	0.1	0.4

Table 5. Chemical mass proportion of reed ash at 550 °C, %.

Component	Limits		Average	
	Winter	Summer	Winter	Summer
SiO_2	65.3–85.5	25.9–48.3	77.8	37.1
Fe_2O_3	0.1–0.8	0.2–1.7	0.3	0.7
Al_2O_3	0.1–1.7	0.1–1.1	0.6	0.6
CaO	3.1–7.3	4.0–11.5	4.4	6.8
MgO	0.4–1.5	1.9–4.9	1.2	3.3
Na_2O	2.0–9.1	0.87–11.0	3.3	3.6
K_2O	1.0–5.7	14.9–31.3	4.3	24.8
Other	1.6 – 19.4	17.3 – 33.5	8.3	23.0

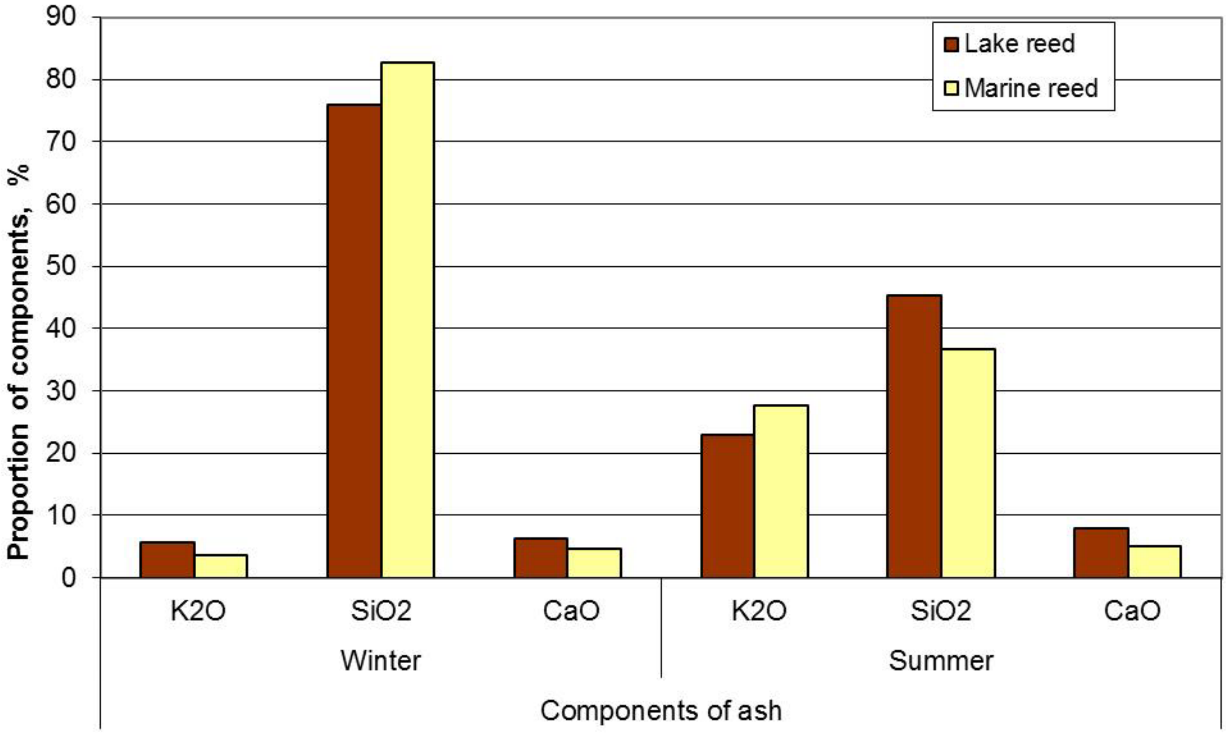

Figure 5. Proportions of chemical components in marine and lake reed ash in winter and summer, %.

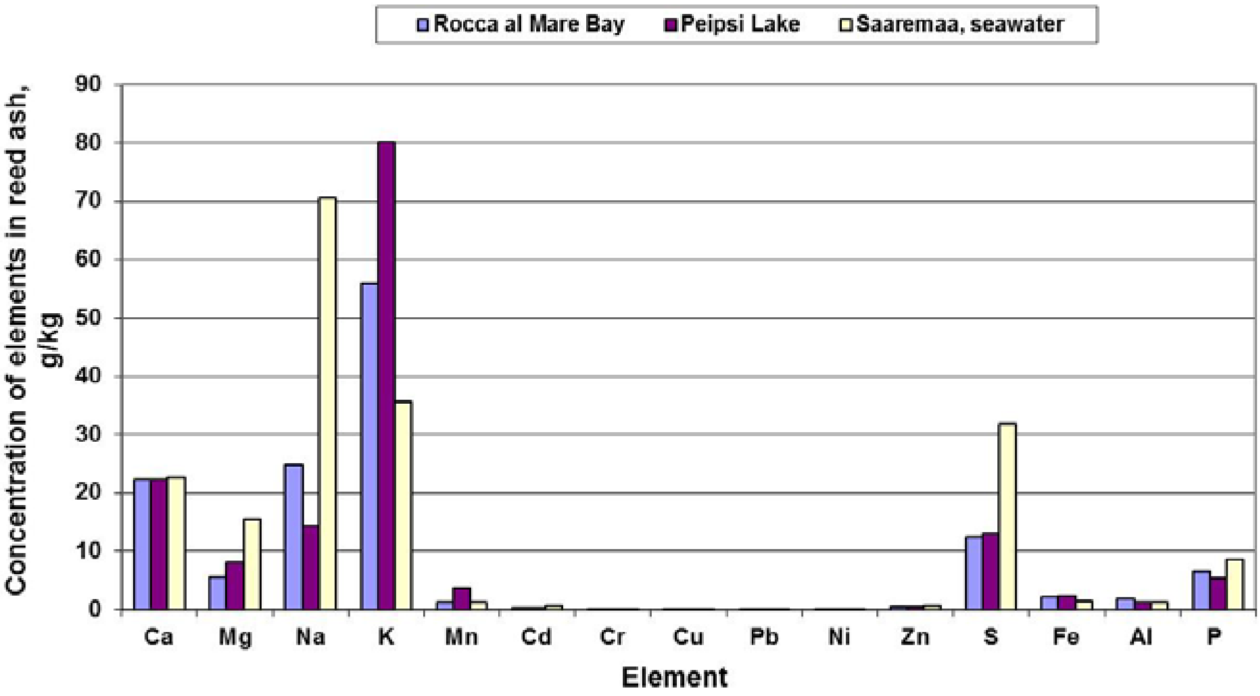

Figure 6. Concentrations of elements in winter reed ash, mg kg^{-1}.

Table 6. Ash fusibility characteristics (°C) of reed harvested in the summer and winter of 2006.

	Sample number (each sample is from a different site)						
	I 06 01	**I 06 02**	**I 06 03**	**I 06 04**	**I 06 05**	**I 06 06**	**I 06 07**
Fusibility characteristics of summer reed							
Deformation temperature, DT	700	650	670	640	730	690	580
Shrinkage temperature, ST	990	1000	1040	960	1030	910	760
Hemisphere temperature, HT	1130	1110	1120	1060	1150	1080	910
Flow temperature, FT	1170	1130	1160	1090	1170	1120	990
Fusibility characteristics of winter reed							
Deformation temperature, DT	800	1040	1220		790		1050
Shrinkage temperature, ST	1240				1040		1200
Hemisphere temperature, HT	1290				1230		1270
Flow temperature, FT	up to 1330 °C, did not melt				1270		1290

DISCUSSION

Reed growing in open water (lakes or the sea) can be cut only in winter when ice allows access for heavy machinery. The same is true of coastal meadows with loose soils. Ice formed in early winter when water levels are high may be too thin to support the weight of machinery at the most suitable time for fuel reed cutting in spring, especially if the water table below the ice has fallen. Deep snow will also prevent efficient reed cutting. Repeated harvesting in combination with a reduced input of nutrients will result in a declining yields, such that reliable harvests cannot be guaranteed. In the worst cases not even 10 % of former yields can be realised (Kask *et al*. 2007). Winter harvest may then be smaller by 20–25% because of leaf shedding and damage due to snow (Table 2).

High moisture proportion (content) reduces the heating value of fuel, increases the volume of flue gases, and makes ignition and combustion less certain. The moisture proportion of energy reed changes significantly over the course of the year (Figure 4). In Estonia the best-quality reed for use as fuel (in this regard) can be harvested over a period of around 90 days a year, in January–March.

Fuel reed is similar to other biomass fuels in that the organic matter (OM) is composed mainly of C, O and H, but the oxygen content in the OM of reed as an annually re-growing plant is somewhat higher and that of carbon and hydrogen a little lower. The content of nitrogen (N), sulphur (S) and chlorine (Cl) in reed samples harvested in winter is low (Table 4).

The ash formed during combustion settle on the surfaces of the furnace, obstructing heat exchange and potentially accelerating high-temperature corrosion. The components that are best-known for accelerating corrosion are compounds of alkali metals, chlorine and sulphur (for example, pyrosulphates). The content of alkali metals in winter harvested reed is lower than in summer harvested reed, which results in significantly higher fusibility temperatures for winter harvested reed. With the low ash-fusibility temperatures of summer reed the probability of ash sintering and fusion is high and the heating surfaces and slagging grates are likely to get blocked with ash particles. Dried summer reed could still be burned in a low-temperature furnace or in a bubbling fluidised bed furnace at ~850 ºC.

Chemical elements that affect ash fusibility temperatures are Ca, K and Na. Reed that is harvested in winter is a better fuel from the point of view of ash composition and quantity. The ash of reed harvested and dried in summer contains significant amounts of alkali metals that negatively affect ash fusibility, the formation of ash deposits on the heating surfaces of boilers and boiler corrosion.

The ash of summer reed fused at temperatures below 1200 ºC and deformation occurred below 800 ºC. In contrast, some samples of winter reed ash did not fuse even at 1350 ºC and only one winter reed ash sample showed evidence of deformation at 800 ºC. Average ash-fusibility temperatures differ by at least 200 ºC between summer and winter reed. Therefore, for use as a boiler fuel, reed should be harvested in winter when nutrients and minerals have been transported to the rhizomes and roots, and leaves have been shed. Ash-fusibility temperature depends on both elemental and component composition. The main elements that influence the fusibility of reed ash are Si, K, Na and Ca. Ash-fusibility temperature is often treated as depending on the total of alkali components or the ratio of alkali and acid components.

Based on our results, common reed is suitable as a fuel in commonly used furnaces. Further tests will be needed to optimise fuel handling and combustion equipment in order to address the variable quality of the material. There may be potential for co-combustion of common reed with other biomass-based fuels.

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