Energietechnik

Aaron Fuller

Effects of biomass combustion on the formation of fly ash and their utilization from suspension-fired boilers

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Effects of biomass combustion on the formation of fly ash and their utilization from suspension-fired boilers

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Aaron Fuller

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Kurzfassung

Aufgrund der durch die Verbrennung fossiler Brennstoffe und damit verbundenen Treibhausgas-, vor allem CO_2, und anderen Schadstoffemissionen entstehenden Umweltprobleme wurden andere Methoden zur Erzeugung sauberer Energie, wie z. Bsp. die Verbrennung von Biomasse gesucht. So hat die Verbrennung hochwertiger Holzpellets in den letzten Jahrzehnten zugenommen. Hochwertige Holzpellets werden weltweit gehandelt und zur Wärme- und Stromerzeugung verbrannt. Auch andere Biomassebrennstoffe wurden erforscht. Untersucht wurden unter anderem die Lieferketten für die Brennstoffversorgung, die Vorbereitung, Handhabung und Zuführung von Brennstoff, die Nachhaltigkeit der Brennstoffbeständigkeit und die Nachrüstung von Kesseln. Die Ergebnisse dieser Studien lieferten Informationen zur Durchführbarkeit, Wirtschaftlichkeit und Wirksamkeit der Verbrennung von Biomassebrennstoffen in Stromerzeugungsanlagen. Die Charakterisierung der Rückstände stand jedoch nicht im Vordergrund. Daher ist wenig über die Produktqualität der durch die Verbrennung von Biomasse erzeugten Flugasche bekannt.

Diese Dissertation behandelt die Charakterisierung von Biomasse-Flugaschen, die in Staubfeuerungsanlagen (der am häufigsten verwendeten thermischen Umwandlungstechnologie) entstehen. Die auf Grundlage der Literaturrecherche am besten geeigneten Biomasse Brennstofftypen wurden für diese Arbeit verwendet. Die Auswirkungen von Änderungen der Verbrennungsbedingungen, z. B. der Verwendung von Additiven und der Einführung von Brennern zur NOx Reduzierung in Kombination mit Ausbrandluft, auf die Bildung von Flugasche und deren Qualität wurden untersucht. Diese Änderungen wurden mit der Verbrennung von Biomasse unter herkömmlichen Bedingungen verglichen. Die Software FactSage 7.1 wurde verwendet, um ihr Potenzial für die Vorhersage von Mineralphasen in der Asche bei unterschiedlichen Eingangsparametern zu ermitteln. Dies erwies sich als äußerst nützlicher Ansatz, insbesondere für Biomasseasche, oder das Verfahren könnte für Brennstoffgemische verwendet werden. Die Flugasche wurde durch chemische Analysen der Haupt- und Nebenelemente sowie des Auslaugungsverhaltens (Umweltaspekt) charakterisiert. Die Partikelgrößenverteilungen der Flugasche wurden bewertet. Röntgenpulverdiffraktometrie und Mikro-Raman-Spektroskopie wurden verwendet, um die Mineralphasen qualitativ zu bewerten. Rasterelektronenmikroskop und energiedispersive Röntgenstrahlen wurden verwendet, um die morphologischen Eigenschaften der Flugascheteilchen zu beobachten. Auswertungsversuche wurden durchgeführt, um das Verhalten der Flugasche zu charakterisieren. Die Flugaschequalitäten wurden auf ihre Eignung für eine Putzgrundierung getestet. Eine Flugasche-Qualität erwies sich für den Einsatz in Außenputzen als geeignet. Der Ersatz von Zement durch eine hochwertige Flugasche in Putzmischungen oder anderen alternativen Bindemitteln, möglicherweise in erheblichen Mengen, könnte zur Verringerung der CO_2 Emissionen aus der Zementindustrie führen, da weniger Zement benötigt würde.

Die Ergebnisse liefern wertvolle Informationen für Kraftwerkspersonal, Aschemanager und Behörden. Darüber hinaus tragen die Ergebnisse zu einem nachhaltigen Aschemanagement der durch Verbrennung von Biomasse in Brennstoffkesseln entstehenden Flugasche bei, was die soziale Verantwortung und Kreislaufwirtschaft unterstützt.

Abstract

Biomass combustion was sought as environmental concerns grew from the combustion of fossil fuels due to the increase in greenhouse gas emissions, mainly CO_2 and other pollutants. Thus, the combustion of biomass increased in the last decades. High-quality wood pellets are traded worldwide and combusted for heat and power production. Research for other biomass fuels occurred too. The earlier research mostly focused on boiler performance issues, such as the slagging, fouling, corrosion, and efficiency. Also, fuel supply chain, fuel preparation, handling, and feeding, fuel sustainability, boiler retrofitting needs, among others, were studied. However, the characterization of the residues was not a central, primary focus. Therefore, less is known about the by-product quality of the generated fly ashes from biomass combustion.

The work reported in this dissertation explored characterizing biomass fly ashes produced by pulverized fuel boilers (the most commonly used thermal conversion technology). The most suitable biomass fuel types based on the literature review were used for the work. The impact of changes in operational combustion conditions, e.g., additive use and introduction of low-NOx burners combined with over-fire air, on the formation of fly ash and its quality were studied. Those changes were compared to biomass combustion in conventional air conditions. The FACTSage 7.3 software was used to evaluate its potential in predicting mineral phases in ashes when input parameters are varied. The use of FACTSage was found to be an instrumental approach, especially for biomass ashes, or the method could be used for fuel blends. The fly ashes were characterized by chemical analyses of major and minor elements and leaching behavior (environmental aspect). The particle size distributions of the fly ashes were evaluated. X-ray powder diffraction and micro-Raman spectroscopy were used to qualitatively evaluate the mineral phases. Scanning electron microscope and energy dispersive X-ray were used to observe the morphological characteristics of the fly ash particles. Performance tests were conducted to characterize the behavior of the fly ashes and fly ash qualities were tested for a constituent of a render base coat. One fly ash quality was proven viable for use in external renders. The substitution of high-quality fly ash for cement in render mixtures or other alternative binders, possibly in significant amounts, could contribute to mitigating CO_2 emissions from the cement manufacturing process, as less would be needed. The results provide valuable information for power plant personnel, ash managers, and authorities. Also, the findings contribute to sustainable ash management from the combustion of biomass in pulverized fuel boilers, which supports social responsibility and a circular economy.

Contents

1 Introduction and overview ... 1
1.1 Motivation ... 1
1.2 Why the thermal utilization of biomass fuels ... 2
1.3 Co-firing technology mostly used for biomass combustion ... 6
1.4 Coal combustion by-products (CCPs) and pozzolanic materials that replace cement use ... 8
1.4.1 Cement production: past, present, and concerns ... 8
1.4.2 Pozzolanic materials that replace cement use ... 10
1.5 Importance of using fly ash from thermal conversion processes ... 11
1.5.1 The beginnings of modern fly ash use ... 11
1.5.2 Significance of continued use of fly ash ... 12
1.6 Starting situation to begin the work ... 18
1.7 Tasks and objective ... 19
1.8 Structure of Work ... 20
1.9 Already published articles of this work ... 21
2 Background- literature study ... 22
2.1 Fly ash origin, formation, and collection ... 22
2.1.1 Ash-forming matter in solid fuels ... 22
2.1.2 Fly ash formation from the combustion of solid fuels ... 24
2.1.3 Collection of fly ash ... 27
2.2 Fly ash properties ... 29
2.2.1 Fly ash physical and morphological characteristics ... 30
2.2.2 Physical properties of different fly ash types ... 31
2.2.3 Fly ash chemical properties characteristics ... 32
2.3 Biomass fuels and some factors impacting selection for tests ... 36
2.3.1 Biomass fuels ... 36
2.3.2 Considerations of appropriate fuels for the work ... 37
2.3.3 Fly ash mineralogical characteristics and considerations ... 38
2.4 Background for fly ash uses ... 47
2.4.1 Consideration of fly ash use in major standardized applications ... 49
2.4.2 Non-standardized uses ... 52
2.4.3 Ash beneficiation ... 53
2.5 Background of reasons for chemical limits to use fly ash ... 54
2.6 Specifications and Standards ... 59
2.7 Potential influences and impacts of operational changes on fly ash quality ... 66
2.7.1 Boiler retrofitting with low-NOx burners combined with over-fire air and SCR installation and the potential impact on fly ash quality ... 66
2.7.2 Use of alumina-silicate additives in thermal power plants and potential impact on fly ash quality ... 70
3 Power plant and research facilities, test programs, methods, and materials ... 80
3.1 Industrial-scale power plant general information ... 80
3.1.1 Fly ash collection at the industrial-scale facility ... 81
3.2 Pulverized fuel pilot-scale test facility ... 81
3.2.1 General information overview ... 82
3.2.2 Coal fuel preparation and milling ... 83
3.2.3 Biomass fuel preparation and milling ... 83
3.2.4 Fly ash collection at the pilot-scale test facility ... 84
3.3 Small-scale atmospheric combustion reactor ... 84
3.3.1 General information overview ... 84
3.3.2 Fuel milling ... 86

3.4 Test programs 87
3.4.1 Small-scale atmospheric combustion reactor (BTS) test settings........ 88
3.4.2 Pulverized fuel pilot-scale test facility 91
3.4.3 Industrial-scale power plant 92
3.5 Analyses methods........ 95
3.5.1 Characterization and properties of fuels and ashes 95
3.5.2 Performance testing of fly ashes........ 99
3.5.3 Micro-Raman spectroscopy method........ 105
3.5.4 Leaching behavior for environmental characterization........ 107
3.5.5 Rendering base coat testing........ 107
3.5.6 Boiler gaseous species measurements........ 115
3.5.7 FACTSage® 7.3 chemical equilibrium calculations........ 115
3.5.8 Enrichment factors 117
3.6 Materials and mix compositions for performance testing 120
3.6.1 Materials and preparation........ 120
3.6.2 Specimen curing and storage........ 121
3.6.3 The use of fiber reinforcement 123
3.6.4 Fly ash beneficiation 124
4 Results: fuel characterizations........ 125
4.1 Proximate and ultimate analyses results........ 125
4.2 Major and minor oxides in the fuels' ashes........ 127
4.3 Heavy metal contents in the fuels........ 128
4.4 Evaluation and discussions of fuel analyses........ 129
4.4.1 Evaluation of proximate and ultimate analyses results 129
4.4.2 Major and minor oxides or elements in the fuels' ashes for the different test scales.. 131
5 Results: Effects of an alumina-silicate additive on wood dust fly ash formation and transformation in a small-scale pulverized fuel boiler........ 133
5.1 Chemical characterizations of filter ashes without and with additive addition........ 133
5.2 Morphological characteristics of generated filter ashes without and with alumina-silicate additive addition........ 135
5.3 Mineral characterization of filter ashes generated without and with alumina-silicate additive addition 138
5.4 Micro-Raman spectroscopy analyses of filter ashes with additive addition........ 140
5.5 Behaviors of certain species in filter ashes without and with additive addition........ 142
5.6 Impacts on Cl and Sulfur in the filter ashes 143
5.7 Evaluations and discussions of small-scale tests with an additive 146
5.7.1 Impact of changes in chemical characteristics from the alumina-silicate additive addition 146
5.7.2 Discussion of morphological changes........ 147
5.7.3 Discussion of mineral phases changes 149
5.7.4 Discussion of micro-Raman spectroscopy results........ 150
5.7.5 Discussion of filter ash transformation with certain species 152
5.8 Conclusions of the impact of additive (kaolin) 157
6 Results: Fly ash formation and characteristics from (co)combustion of *Cynara* with a type of Greek lignite (low-rank coal) and pure wood dust combustion in the pilot-scale test facility........ 160
6.1 Ash balance 160
6.2 Chemical analyses of *Cynara* fly ashes generated in the pilot-scale test facility........ 161
6.3 Some compounds in the ash of different sampling locations from *Cynara* tests at the pilot-scale test facility........ 163
6.4 Particle size distributions of *Cynara* fly ashes generated in the pilot-scale test facility 168
6.5 Mineral characterization of *Cynara* fly ashes generated in the pilot-scale test facility........ 169
6.6 Leaching characteristics of *Cynara* fly ashes generated in the pilot-scale test facility 171
6.7 Soundness testing of some fly ash samples from *Cynara* experiments........ 172

6.8 Initial setting time of some fly ash samples from *Cynara* experiments 173
6.9 Evaluations and discussions of pilot-scale *Cynara* tests 173
6.9.1 Impact of changes in chemical characteristics 173
6.9.2 Indications from compounds in different ash sample locations 178
6.9.3 Evaluation of particle size distributions 182
6.9.4 Evaluation of mineralogy of the fly ashes from co-firing *Cynara* 183
6.9.5 Observations from leaching behavior.. 187
6.9.6 Characterizations from performance testing.. 188
6.10 Major and minor oxides in the ESP ash fractions for pure wood dust combustion at the pilot-scale test facility 190
6.11 Conclusions from *Cynara* tests and pure wood dust combustion 191
7 Results: Fly ash formation and their utilization from wood dust (co-)combustion in an industrial scale suspension-fired boiler emphasizing changing combustion conditions 193
7.1 Chemical oxides analyses of the fly ashes 193
7.2 Relative enrichment of elements in the fly ashes 194
7.3 The particle size distribution of the fly ashes.. 194
7.4 Heavy metal contents and leaching behavior of fly ashes.. 196
7.5 Mineral characterization of fly ashes 198
7.6 Boiler gaseous measurements and thermodynamic equilibrium calculations predicting mineral phases' stability.. 202
7.7 Comparisons to EN 450-1 207
7.8 Evaluations and discussions 208
7.8.1 Impacts from chemical characterization... 208
7.8.2 Observations from enrichment factors calculations 212
7.8.3 Assessment of heavy metal behavior 214
7.8.4 Mineral phase characterizations of the fly ashes... 216
7.8.5 Assessments of gas measurements and thermodynamic calculations 217
7.8.6 Qualitative assessment of increased free lime and calcium minerals on potential atmospheric CO_2 sequestration (carbonation reactions).. 220
7.8.7 Evaluations of comparison to EN 450-1 226
7.8.8 A high-value utilization option of the wood dust II fly ash....................................... 230
7.8.9 Evaluation of the fly ashes' pastes (a consideration for mortar use).......................... 235
7.8.10 Conclusion of the industrial-scale fly ash test results.. 260
8 Conclusions, recommendations, and future work 263
8.1 Overview summary 263
8.2 Conclusions 266
8.3 Recommendations and Future work... 271
9 Appendices 275
10 References 290

Nomenclature and Symbols

Latin Symbols

Symbols	Units	Meaning
A	mm^2	cross sectional area
A.I.	-	activity index ratio
c_i	mg/l, µg/l	mass concentration of a material
$E_{\sigma s}$	N/mm^2	modulus of elasticity
E_{co}	N/mm^2	modulus of elasticity value given
$EF_{Tot,i,A}$	-	factor for total mass stream increase of *i* in ash/byproduct
F	N	force
$f_{by,i}$	-	byproduct dilution
f_c	MPa (N/mm^2)	specified compressive strength
f_{ck}	MPa (N/mm^2)	characteristic compressive strength
f_{cm}	MPa (N/mm^2)	measured compressive strength
f_{cm0}	MPa (N/mm^2)	compressive strength value given
f_t	MPa (N/mm^2)	tensile strength
f_{fl}	MPa (N/mm^2)	flexural strength
f_i	-	molecular mass ratio of oxide to element (oxide factor)
H	mm	height
H_H	kJ/kg	higher calorific value
H_L	kJ/kg	net calorific value/lower calorific value
k_1	-	coefficient factor for coarse aggregate
k_2	-	coefficient factor for mineral admixtures
K_c	-	proportion of coal being fired
K_i	-	proportion of co-firing materials
L (l)	mm	length
M	kg, g	mass
$\dot{M}$	kg/s, t/h	mass flow rate
M_M	kg/kmol	molar mass
n	-	air stoichiometric ratio
n_i	mol	amount of substance
$\dot{\boldsymbol{n}}_{\boldsymbol{\imath}}$	mol/s	molar flow
P	MW_{el}	power
ppmv	-	parts per million volume
$\dot{\boldsymbol{Q}}$	W	heat flow
RE	-	relataive enrichment factor
RH	[%]	relative humidity
t	hours or days	time
$\dot{\boldsymbol{V}}$	m^3/h	volume flow rate (STP)
W	mm	width
w_c	kg/m^3	unit mass of concrete
X_i	g/g, kg/kg, mg/kg, %	mass fraction; mass percent of indicated compound
y	m^3/m^3, Vol.-%	volume fraction

Greek Symbols

Symbols	Unit	Meaning
$\boldsymbol{\alpha_E}$	-	value for aggregate type
β	mg/m^3	mass concentration
ϑ	°C; K	temperature
$\varepsilon_{shr.}$	mm/m	shrinkage strain
σ, σ_s	MPa or N/mm^2	normal stress
σ_{std}	-	standard deviation
δ	mm	axial deformation
γ_i	-	fuel mass fraction of the substance i (C, N, O, S, H, H_2O, A (=ash))
α	-	molar ratio
ν	-	stoichiometric coefficient

Indices and abbreviations subscripted

Symbol	Meaning
c	compressive
diff	difference
el	electric
fixed-c	fixed carbon
GCV	gross calorific value
H	higher
i	variable
L	lower
meas	measured
p	constant pressure
ref	reference
sh(t)	shrinkage at curing time t (days)
t	tensile
th	thermal share

Length sizes

Symbol	Meaning
D	particle size
D_{10}	the diameter having 10 % of the distribution as smaller particle sizes and 90 % as larger particle sizes
D_{50}	the diameter having 50 % of the distribution as smaller particle sizes and 50 % as larger particle sizes
D_{90}	the diameter having 90 % of the distribution as smaller particle sizes and 10 % as larger particle sizes

Abbreviations

Abbreviation	Meaning
A_i	the ash content of co-combustion material according to special provisions of fly ash from co-combustion in EN 450-1
A	Al_2O_3
af	after retrofit
AFt	$3CaO\cdot Al_2O_3\cdot 3CaSO_4\cdot 32H_2O$ (ettringite)
A.I.	activity index ratio
ASR	alkali-silica reaction
ASTM	American Society for Testing Materials
bf	before retrofit
BFG	Blast Furnace Gas
BTS-VR	Brennstoff-Trenn-Stufungs-Verbrennungsreaktor (BTS)
Ca	calcium
C_3A	tricalcium aluminate ($3CaO\cdot Al_2O_3$)
C_4AF	tetracalcium aluminaferrite ($4CaO\cdot Al_2O_3\cdot Fe_2O_3$)
C_2S	dicalcium silicate ($2CaO\cdot SiO_2$)
C_3S	tricalcium silicate ($3CaO\cdot SiO_2$)
c	cement
CCPs	Coal Combustion By-products
CEM I	Portland cement type I
Cl	chlorine
C-S-H/CSH	calcium silicate hydrate gel ($CaO+SiO_2+H_2O$)
d	dry
daf	dry-ash-free
diff	by difference
DüMV	Düngemittelverordnung (Germany)
ECOBA	European Coal Combustion Products Association
EDX	Electron dispersive X-ray
EN	European Norm (standard)
ESP	Electrostatic Precipitator
ETA	European Technical Approval
EU	European Union
F	Fe_2O_3
FA	Fly ash
FGD	Flue gas desulfurization
GHG	Greenhouse gas emissions
h/hr.	hour
H	H_2O
HVFAP	High volume fly ash paste
IFK	Institut für Verbrennungs- und Kraftwerkstechnik (The Institute of Combustion and Power Plant Technology), University of Stuttgart
K	K_2O
KSVA	Kohlenstaubmahl- und Verbrennungsanlage
LAGA	Länderarbeitsgemeinschaft Abfall (Germany)
LOI	loss on ignition
m	mass
M	MgO
max	maximum
mg/l	milligram per liter
N	Na_2O
NOx	nitrogen oxides (NO and N_2O)

Abbreviation	Meaning
O	oxygen
OPC	Ordinary Portland cement
PF	Pulverized fuel
rpm	revolutions per minute
s	second
SEM	Scanning electron microscope
STP	standard temperature pressure (0°C, 1013 mbar)
VM	volatile matter
w	water
W	anionic groups, such as $(OH)^-$ or anions such as Cl^- or F^-
XRD	X-ray powder diffraction
Y	two to four valent ions of Mn^{2+}, Fe^{2+}, Mg^{2+}, Fe^{3+}, Ti^{4+}, or Al^{3+}
Z	charged ions of Al^{3+} or Si^{4+}