

Collins Ndibe

Characterization of torrefied fuels for direct co-firing in large pulverized fuel boilers

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Preface

The present thesis is the result of my work as an academic researcher between February 2012 and September 2017 at the Institute of Combustion and Power Plant Technology, University of Stuttgart. The scientific supervision of the thesis as well as the preparation of this report has been under the guidance of the institute's director, Prof. Günter Scheffknecht, to whom, I would like to express my utmost gratitude.

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Kurzfassung

Biomassen weisen im Vergleich zu Kohle unterschiedliche chemische und physikalische Eigenschaften auf. Dies begrenzt in konventionellen Dampfkraftwerken die Substitution von Kohle durch Biomasse. Um die Nutzung von Biomasse zu fördern, müssen die Zuverlässigkeit, Effizienz und Wirtschaftlichkeit der Feuerungsanlagen mindestens aufrechterhalten werden. Dies muss unter Einhaltung der Emissionsanforderungen und der Berücksichtigung der aktuellen Flexibilitätsanforderungen erfolgen.

Torrefizierung zur Verbesserung der Brennstoffeigenschaften von Biomasse ist eine neuartige Technologie. Sie beinhaltet das Erhitzen von Biomasse in Abwesenheit von Sauerstoff auf eine Temperatur von 200°C bis 300°C. Torrefizierte Biomasse soll bessere Lagereigenschaften, verbesserte Mahlbarkeit, höhere Energiedichten und homogenere Eigenschaften aufweisen.

Die Quantifizierung der Mahlbarkeit von thermisch behandelter Biomasse ist notwendig, um ihre Mahlbarkeit in Kohlemühlen zu beurteilen. Eine verbesserte Mahlbarkeit wird durch die Torrefizierung erreicht. Die Frage, ob dies ausreichend ist, um torrefizierte Biomasse in Kohlemühlen zu zerkleinern, ist derzeit unbeantwortet. Mahlversuche in Großanlagen sind sehr teuer und mit einem hohen Risiko für die Betreiber behaftet. Vor diesem Hintergrund beschäftigt sich ein Teil der vorliegenden Arbeit mit dem Ziel, ein Laborverfahren zur Vorhersage der Mahlbarkeit zu entwickeln und zu validieren. Die durchgeführten Tests reichen von Tests im Labormaßstab bis hin zu industriellen Validierungstests. Die Arbeit untersucht auch den Energieverbrauch in einer typischen Biomasse-Mühle wie der Hammermühle, um das Verbesserungspotential, das durch die Torrefizierung erzielt werden kann, zu bestimmen.

Torrefizierte Biomassepartikel haben eine andere Form und Morphologie als unbehandelte Biomassepartikel. Auch ihre innere Oberfläche und Gesamtporenvolumina sind unterschiedlich. Der Flüchtigengehalt der Biomasse nimmt infolge der Torrefizierung ebenfalls ab. Die Partikelgröße und der Flüchtiganteil beeinflussen signifikant die Flüchtigensfreisetzung und somit das Zünden und die Stabilität der Flamme an der Brennerwurzel. Die Flammenzone der Flüchtigenverbrennung ist wichtig für die

Flammenstabilität sowie für die Bildung und primäre Minderung von Schadstoffen wie NO_x. In den experimentellen Arbeiten werden verschiedene torrefizierte und nicht torrefizierte Biomassen untersucht. Es wurden Versuche zur Pyrolyse sowie gestufte und ungestufte Verbrennungsversuche durchgeführt, um die Schadstoffbildung und -reduktion zu untersuchen. Die Entgasungsexperimente liefern Informationen über die Gasphasenzusammensetzung, den Massenumsatz und zur Stickstoffverteilung in flüchtigen Bestandteilen und Koks. In Laboranlagen wird die Verbrennung von torrefizierter Biomasse, von Kohle und von Mischungen beider Brennstoffe bei unterschiedlichen Verbrennungsbedingungen untersucht. Weitere Versuche werden an einer 500 kW-Kohlenstaubverbrennungstestanlage sowie an einer industriellen Kraftwerksfeuerung durchgeführt.

Die Mahlergebnisse zeigen, dass der herkömmliche Hardgrove-Index zur Beschreibung der Mahlbarkeit von torrefizierter und nicht torrefizierter Biomasse nicht geeignet ist. Es werden dafür Anpassungen an das Standardverfahren vorgenommen, um das Verfahren insbesondere für thermisch behandelte Biomasse zu adaptieren. Die Anpassungen beziehen sich auf die Probenmenge für die Bestimmung, die Partikelgrößenkriterien zur Definition der Mahlbarkeit und die Erzeugung der Mahlbarkeitskalibrierkurve.

Die angepasste als TTBTGI für *thermally treated biomass grindability index* bezeichnete Methode wird für eine Reihe von torrefizierten Biomassematerialien getestet und validiert. Das Verfahren zeigt eine gute Wiederholbarkeit innerhalb von ± 2 TTBTGI-Einheiten, analog zu der herkömmlichen Charakterisierungsmethode, dem Hardgrove-Index. In einer für Biomasse typischen Hammermühle kann der Vorteil der Torrefizierung in Bezug auf den geringeren Mahlenergieverbrauch und die Feinheit der Produktausbeute für die torrefizierte Biomasse gezeigt und quantifiziert werden.

Pyrolysetests mit torrefiziertem und nicht torrefiziertem Holz zeigen, dass mehr als 90% des Brennstoffstickstoffs mit den flüchtigen Bestandteilen freigesetzt werden. Der nach der Pyrolyse im Koks vorhandene Stoffstickstoffanteil ist für beide Brennstoffe sehr niedrig und liegt unter 6%. Der entsprechende Vergleichswert bei Kohle liegt bei 75%. Im Vergleich zu Kohlen wird die Biomasseverbrennung durch homogene Gasphasenreaktionen dominiert.

Primäre NO_x -Minderungsmethoden wie die Luftstufung sind aktiver in der homogenen Reduktion von Stickstoff-Zwischenprodukten in der Gasphase. Neben dem Brennstoffstickstoffgehalt wird die NO_x -Bildung auch durch die Flüchtigensfreisetzung und damit die Flammenstruktur beeinflusst. Ebenfalls beeinflussen die Partikelgröße und die Aerodynamik am Brenner die Flammenstruktur. Wenn sich größere Biomassepartikel langsamer aufwärmen, kommt es zu einer verzögerten Freisetzung von flüchtigen Bestandteilen und Stickstoff-Zwischenprodukten. In Abhängigkeit von lokalen Stöchiometrien werden die Stickstoff-Zwischenprodukte zu NO_x oxidiert oder zu N_2 reduziert. Die Optimierung der Mischungsintensitäten sowie der Partikelgrößenverteilung kann eine effektive Ausnutzung der Flammenzone für die NO_x -Reduktion sicherstellen. Torrefizierung in dieser Hinsicht ist positiv für Biomassen, da der Grad der Feinheit aufgrund der besseren Mahlbarkeit verbessert ist. Brenner- und Brennkonzeppte müssen so ausgelegt sein, dass das primäre NO_x -Reduktionspotenzial optimiert wird, besonders im Brennernahfeld.

Abstract

Biomass fuels have variable chemical and physical properties which differ significantly from that of coal. This places limits on the amount of coal that can be substituted with biomass in conventional coal boilers. In order to encourage the use of biomass fuels, the reliability, efficiency and economics of boilers should be at least maintained. This is in addition to maintaining the emissions requirements and being able to fulfill flexibility demands.

Torrefaction for upgrading the fuel properties of biomass is a novel technology. Torrefaction involves heating of biomass in the absence of oxygen to a temperature of 200°C to 300°C. Torrefied biomass is reported to have better storage properties, improved grindability, higher energy densities and more homogenized properties.

Quantifying the grindability of thermally treated biomass is necessary for predicting its performance in coal milling systems. While there are improvements in grindability brought about by torrefaction, at this time the question of whether the improvements are sufficient enough for torrefied biomass to be fractionated in typical coal mills is still unanswered. For utilities that have tested torrefied biomass, the practice is to perform large scale mill trials which are expensive and time consuming. This work evaluates the grindability of densified torrefied biomass in industrial coal mills with the aim to develop and validate a lab procedure for predicting the grindability in such mills. Tests performed range from lab-scale to industrial-scale validation tests, utilizing various fractionation devices and mechanisms. The work also examines grinding performance in a typical biomass mill such as the hammer mill in order to quantify the benefit gained by torrefaction.

Torrefied biomass particles have a different shape and morphology compared to non-treated biomass particles. Their particle shape descriptors (aspect ratios and sphericities), inner surface areas, and total pore volumes are different compared to non-torrefied biomass. The volatility of biomass also decreases as a result of torrefaction. Particle size and volatility significantly impact the structure of the volatile flame in the near burner region. The near burner volatile flame zone is important for flame stability as well as the formation and primary control of NO_x.

The experimental work which involved de-volatilization and combustion tests examined various biomass fuels including torrefied biomass in co-firing configurations with coal as well as mono-firing test cases. The de-volatilization tests provide information on the gas phase composition, mass release and nitrogen distribution in volatiles and char. The combustion tests were performed in a 20kW reactor, a 500kW test rig while large scale co-firing trials were done in an industrial utility boiler.

The milling results show that the HGI method is flawed when applied for the grindability of biomass materials. Three adaptations were applied to the standard method to extend it to thermally treated biomass materials. These adaptations relate to the amount of sample for the determination, the particle size criteria for defining grindability and the generation of the grindability calibration curve. The adapted approach, termed thermally treated biomass grindability index, TTBTGI was then substantially tested and validated for a range of torrefied biomass materials. The method showed good repeatability within ± 2 TTBTGI units, analogous to requirements of the HGI characterization method. In a typical biomass hammer mill, the advantage of torrefaction can be seen and quantified in terms of lower milling energy consumption and the fineness of product output for the torrefied biomass.

De-volatilization tests show mass release to be higher for non-torrefied wood compared to torrefied wood (with both being much higher than coal). For torrefied and non-torrefied biomass, more than 90% of the fuel nitrogen is released with the volatile matter. The retention of fuel nitrogen in char is for both fuels below 6% (much lower than that of bituminous coal that was about 75%). Compared to coals, biomass combustion is dominated by homogeneous gas phase reactions. Primary NO_x control techniques such as air-staging are more active in the volatile gas phase homogeneous reduction of fuel nitrogen intermediates, making higher volatile fuels potentially ideal for NO_x reduction by this method. In addition to the fuel nitrogen content, NO_x formation is also influenced by flame structure and flame structure by fuel volatility, particle size and burner aerodynamics. As larger biomass particles heat-up slower, particle breakthrough of the initial volatile combustion zones may occur leading to further volatile release (with accompanying release of nitrogen intermediates). Depending on local stoichiometries, the volatile-nitrogen intermediates will be oxidized to NO_x or reduced to N₂.

Optimization of swirling intensities as well as particle size distribution will ensure effective utilization of the volatile flame zone for implementing primary NO_x control techniques like air-staging. Torrefaction in this regard is positive for biomass as the degree of fineness is improved due to better grindability. Burner and firing concepts have to be adapted in order to optimize the primary NO_x reduction potential, especially in the near burner region.

Nomenclature- Latin Alphabets/ Formula Symbols

Symbol	Unit	Meaning
A	m ²	Area
D _x	μm	Diameter at which x% of the sample's mass (for sieve analysis) or volume (for malvern analysis) is comprised of particles with a diameter less or equal to the measured value
E	J	Energy
gbp	g/rev	Equilibrium net grams of material per revolution of the ball mill produced according to the Bond work index
H _o	MJ/kg	Gross calorific value
H _u	MJ/kg	Net calorific value
K	various	Characteristic material constant
L	m	Length
m _x	kg	Mass of substance x
M	Nm	Torque
N	(-), min ⁻¹	Air ratio, mill revolution number
η _C	%	Collection efficiency
η _{MR}	(-)	Mass release
η _{N, char}	%	Fraction of nitrogen retained in the char
P	N/m ²	Pressure
P	m	Perimeter
T	K	Temperature
T	s	Time
T	s	Residence time
P	kg/m ³	Density
u	m/s	Velocity
μ _{ED}	(-)	Energy densification as a result of torrefaction
μ _M	(-)	Mass loss as a result of torrefaction
μ _{VM}	(-)	Volatile matter loss as a result of torrefaction
V	m ³	Volume
Ṁ	m ³ /s	Volume flow at 1,01325bar and 273,15K
W _i	(kWh/ton)	Work index
X	μm	Particle size
X	kg/kg	Mass fraction
Y	(-)	Volume fraction
γ _x	wt. %	Mass fraction of substance x in fuel

Nomenclature- Abbreviation

Abbreviation	Full name
AWL	Anhydrous Weight Loss
APH	Air Pre-Heater
BET	Brunauer–Emmett–Teller
BWI	Bond Work Index
COD	Chemical oxygen demand
EEG	Erneuerbare-Energien-Gesetz (German renewable energy act)
ESP	Electrostatic Precipitator
EU	European Union
FGR	Flue Gas Recirculation
FGD	Flue gas desulphurization unit
FTIR	Fourier-Transform Infrared Spectroscopy
G	Grinding criterion
HGI	Hardgrove Grindability Index
HGI-SRS	Hardgrove Grindability Index, Standard Reference Samples
HSE	Health Safety and Environment
ICP-OES	Inductively Coupled Plasma-Optical Emission Spectroscopy
LNB	Low NO _x Burner
MSW	Municipal Solid Waste
NDIR	Non-Diffractive Infrared Spectroscopy
OFA	Over-Fire Air
PMI	Impact Grindability Index (German: Prallmahl Index)
RDF	Refuse Derived Fuel
RR model	Rosin Rammler model
SCR	Selective Catalytic Reduction
SPS	Signal Processing System
SRF	Solid Recovered Fuel
TD	Torrefaction Degree
TTBGI	Thermally Treated Biomass Grindability Index
waf	Water and ash free
wf	Water free

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