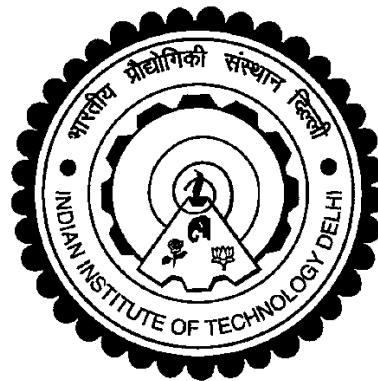


Characterization of Biomass Pellets

MANISH GUPTA



DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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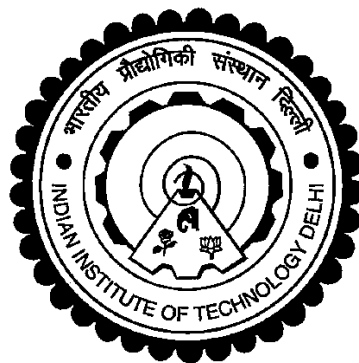
MANISH GUPTA

Department of Mechanical Engineering

Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to

My Mother Mrs. Meena Devi and father Mr. Shree Krishana Prasad Gupta,

and

to my wife Mrs. Priya, daughter Kavya Shree and son Shivansh

CERTIFICATE

This is to certify that the thesis titled “Characterisation of Biomass Pellets”, submitted by Manish Gupta, to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, is a bona-fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Sangeeta Kohli
Professor
Dept. of Mechanical Engineering
IIT Delhi, 110 016

Prof. Anjan Ray
Professor
Dept. of Mechanical Engineering
IIT Delhi, 110 016

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This achievement is not mine alone but belongs equally to my entire family, who have stood by me in every step of this academic journey.

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Manish Gupta

ABSTRACT

Biomass continues to be relevant in the energy needs the world, especially developing nations. A considerable part of biomass is in powdery form such as agricultural residues, obtained after threshing and sawdust, which is a waste from timber industry. Transportation of biomass in powdery form can be cumbersome and also costly. Combustion of powdery biomass in many applications can be inefficient, and highly polluting. Thus, pelletization is being looked upon as an important process in the effective use of biomass.

While a large body of literature is available on many aspects of pelletization and their combustion, most studies on their combustion characteristics carry out combustion of these pellets in controlled furnaces. These studies are relevant to use of these pellets in the furnace of an industry fuelled by these pellets. However, there are some applications using pellets like cookstoves of various sizes which may have natural convection induced flow of combustion air, where every pellet gets ignited by the neighbouring pellet in an environment having temperatures considerably lower than those in industrial furnaces. Such studies are not found in the literature. Moreover, currently commercial pellets are available at a pellet density of around 1200 kg/m^3 . Studies on effect of density of a pellet on its combustion characteristics both as a single pellet and in fixed bed are very limited. The present work aims to bridge this gap by conducting the combustion experiments on single pellets as well as fixed bed mode in ambient conditions for different density pellets with different biomass type and at different dimensions. The experimental work was carried out in three phases.

Prior to combustion experiments, it was considered desirable to characterize the selected biomass. This constituted phase-1 of experimentation. Three types of biomass were procured from the market for preparing in-house pellets. Besides, three types of commercially available pellets were procured. The biomass used in preparation of these pellets was also characterized by crushing these pellets. Thus, in Phase-1, six types of biomass were tested for proximate, ultimate and thermogravimetric analysis. Using TGA and DTG data for the selected biomass types, many parameters relevant to combustion of biomass were determined.

The heating value of biomass was also determined experimentally. Review of literature on estimation of higher heating value (HHV) showed that most correlations used data on dry basis, while retaining ash as a constituent of the biomass. Since ash is inert and does not contribute to the heating value of the biomass, it was considered desirable to develop such correlations using data on dry ash-free basis. 14 such correlations were determined using ultimate analysis data on dry ash-free basis or using proximate analysis data on dry ash-free basis or using both

of these. Most of them had much better statistical indicators as compared to correlations from the literature. The best goodness of fit was obtained from a quadratic correlation using elemental carbon and hydrogen on dry ash-free basis.

The preparation of pellets using manual press and then a Universal Testing Machine (UTM) also constituted phase-1, as did the testing of physical and mechanical properties. Twenty-seven types of pellets were made in-house using three different biomass types at three different diameters using three different loads resulting in different densities. These experiences showed the importance of heating the die. Hence all subsequent pellets were prepared after heating the die to 60°C. The density of pellets was measured, and the pellets were tested for their compressive strength. The commercial pellets were also tested for their durability.

Phase-2 of experiments involved single pellet combustion in ambient conditions by igniting them on a grate using a lighter. The measurements included mass of the pellet with time and CO concentration at the exit of enclosure, where combustion was carried out. The data collected was analysed to determine the effect of density, diameter and type of biomass on the mass loss rate and emissions. Besides experiments, simulation of devolatilization of single pellet in an inert environment was also carried out using OpenFoam software with reasonable agreement of the simulation predictions with measured data. Density, diameter and biomass of the pellet were found to play an important role in the mass loss rate and CO emissions. Larger density pellets showed higher actual mass loss rate but lower normalised mass loss rate. They also resulted in lower peak in CO emissions. Groundnut shell did not exhibit favourable behaviour in these experiments with frequent need to reignite the pellet.

In phase-3 of the experiments, the combustion of commercially available pellets was carried out in a fixed bed in the configuration of a Top-Lit Up Draught (TLUD) cookstove. Here, the mass of the fuel bed, the flame temperature at the exit of cookstove, CO and PM emissions were measured in real time. The data was analysed for dependence of burn rate in flaming and char combustion periods on pellet diameter, length and type of biomass.

A methodology to determine burn rate in fixed bed TLUD configuration from single pellet experiments has been proposed with very encouraging results. This methodology can be refined with more focussed data collection and determining single pellet burn rate as a function of relevant parameters.

Development of ignition pellets made of sawdust and candle wax for quick ignition of a fixed bed of pellets has also been reported. These pellets get ignited in a second and burn long enough for ignition of the bed. The simulation results for fixed bed combustion of pellets in TLUD mode using an existing code have also been reported.

सार

दुनिया की ऊर्जा आवश्यकताओं की पूर्ति में बायोमास आज भी विकासशील देशों में महत्वपूर्ण भूमिका निभा रहा है। कई प्रकार के बायोमास, जैसे कि कृषि अवशेष, थ्रेशिंग के बाद प्राप्त सामग्री तथा लकड़ी उद्योग से निकलने वाला बुरादा छोटे कणों के रूप में मिलते हैं। इस प्रकार, बुरादे के रूप में बायोमास की ढुलाई कठिन और महंगी होती है। इसके अतिरिक्त, कई प्रकार के उपयोगों में पाउडर बायोमास का दहन किया जाता है, जिससे अत्यधिक प्रदूषण उत्पन्न होता है। इन समस्याओं के समाधान के लिए बायोमास का पेलेटाइजेशन एक प्रभावी तकनीक के रूप में उभरकर सामने आया है।

पेलेटाइजेशन तथा दहन से संबंधित अनेक अध्ययन उपलब्ध हैं, किंतु अधिकांश शोध नियंत्रित औद्योगिक भट्टियों में इन पेलेटों के दहन पर केंद्रित रहे हैं। ऐसे अध्ययन मुख्यतः औद्योगिक भट्टियों में इनके उपयोग के संदर्भ में प्रासंगिक हैं। इसके विपरीत, कुछ अनुप्रयोग—जैसे कि विभिन्न आकारों के चूल्हे ऐसे भी हैं, जिनमें दहन के लिए वायु का प्रवाह प्राकृतिक संवहन के कारण होता है। इन स्थितियों में प्रत्येक पेलेट पड़ोसी पेलेट से अपेक्षाकृत कम तापमान वाले वातावरण में प्रज्वलित होता है, जो औद्योगिक भट्टियों से भिन्न परिस्थितियाँ उत्पन्न करता है। इस प्रकार के अध्ययन साहित्य में बहुत सीमित हैं। इसके अतिरिक्त, वर्तमान में उपलब्ध व्यावसायिक पेलेटों का घनत्व लगभग १२०० किलोग्राम प्रति घन-मीटर होता है। एकल पेलेट के दहन अथवा फिक्स्ड-बेड के रूप में कई पेलेटों के दहन पर पेलेट के घनत्व के प्रभाव पर भी सीमित ही शोध उपलब्ध है। इस शोध का उद्देश्य उपरोक्त विषयों पर ध्यान देना है, जिससे उनके सन्दर्भ में अधिक जानकारी पाई जा सके। इस शोध में किए गए प्रयोगों को तीन चरणों में विभाजित किया गया है।

दहन के प्रयोगों से पहले चयनित बायोमास के उपयुक्त गुणों का आकलन किया गया। इसके लिए बाज़ार से तीन प्रकार के बायोमास खरीदे गए जिनसे प्रयोगशाला में पेलेट तैयार किए गए। इसके अतिरिक्त बाज़ार में मिलने वाले तीन प्रकार के पेलेट भी खरीदे गए। इन पेलेटों को पीस कर उनके मूल बायोमास के गुणों का भी आकलन किया गया। इस प्रकार कुल छह प्रकार के बायोमास का प्रॉक्सिमेट, अल्टीमेट तथा थर्मो-ग्रेविमेट्रिक विश्लेषण (टीजीए) किया गया।

टीजीए तथा डीटीजी डेटा के आधार पर बायोमास के दहन से संबंधित विभिन्न मापदंड निर्धारित किए गए। साथ ही बायोमास का ऊष्मीय मान भी प्रयोगात्मक रूप से निर्धारित किया गया। साहित्य की समीक्षा से यह पाया गया कि ऊष्मीय मान निकालने के अधिकांश सह-संबंध (कोरिलेशन) बायोमास के गुणों के आँकड़ों का शुष्क आधार पर उपयोग करते हैं अर्थात् राख भी उसमें सम्मिलित होती है, जबकि राख

निष्क्रिय होती है और ऊष्मीय मान में योगदान नहीं करती। इसलिए शुष्क व राख-मुक्त आधार पर सह-संबंध (कोरिलेशन) विकसित करना अधिक उपयुक्त माना गया।

इस अध्ययन में शुष्क व राख-मुक्त आधार पर चौदह सह-संबंध विकसित किए गए, जिनमें अल्टीमेट विश्लेषण तथा प्रॉक्सिमेट विश्लेषण दोनों प्रकार के आँकड़ों का उपयोग किया गया। इन सह-संबंधों के सांख्यिकीय संकेतक साहित्य में उपलब्ध सह-संबंधों की तुलना में बेहतर पाए गए। विशेष रूप से शुष्क व राख-मुक्त आधार पर मौलिक कार्बन और हाइड्रोजन का उपयोग करके विकसित द्विघात सह-संबंध ने सर्वोत्तम पाया गया।

पेलेटों को हस्तचालित प्रेस की सहायता से बनाया गया तथा उनकी संपीड़न (कम्प्रेसिव) शक्ति का परीक्षण यूनिवर्सल टेस्टिंग मशीन द्वारा किया गया। तीन प्रकार के बायोमास, तीन व्यास के पेलेट तथा पेलेट बनाने के लिए मशीन पर तीन विभिन्न भारों का उपयोग करके कुल सत्ताईस प्रकार के पेलेट बनाए गए, जिनसे विभिन्न घनत्व के पेलेट प्राप्त हुए।

प्रयोगों से यह स्पष्ट हुआ कि पेलेट निर्माण के दौरान साँचे को गर्म करना अत्यंत महत्वपूर्ण है। इसलिए सभी पेलेट साँचे को ६० डिग्री सेल्सियस तापमान तक गर्म करने के बाद ही बनाए गए। प्रत्येक पेलेट का घनत्व मापा गया तथा उनकी संपीड़न शक्ति का परीक्षण किया गया। साथ ही बाज़ार से खरीदे गए पेलेटों के टिकाऊपन का भी मूल्यांकन किया गया।

दूसरे चरण में परिवेशीय परिस्थितियों में एकल पेलेट को जाली पर रखकर लाइटर की सहायता से प्रज्वलित किया गया। प्रयोग करते हुए पेलेट का द्रव्यमान तथा दहन कक्ष से निकलने वाली कार्बन मोनोऑक्साइड की सांद्रता को समय के साथ मापा गया। प्राप्त आँकड़ों का विश्लेषण करके पता लगा गया कि पेलेट के द्रव्यमान के घटने की दर और उत्सर्जन इन तीन कारकों - पेलेट घनत्व, व्यास तथा बायोमास प्रकार - पर कैसे निर्भर करता है।

इसके अतिरिक्त ओपनफोम (OpenFOAM) सॉफ्टवेयर का उपयोग करते हुए निष्क्रिय वातावरण में एकल पेलेट के डीवोलेटिलाइजेशन का संख्यात्मक अनुकरण भी किया गया, जिसके परिणाम प्रयोगात्मक आँकड़ों के साथ संतोषजनक सामंजस्य में पाए गए। परिणामों से स्पष्ट हुआ कि पेलेट का घनत्व, व्यास तथा बायोमास प्रकार पेलेट के द्रव्यमान के घटने की दर और कार्बन मोनोऑक्साइड उत्सर्जन को महत्वपूर्ण रूप से प्रभावित करते हैं। अधिक घनत्व वाले पेलेट में वास्तविक द्रव्यमान के घटने की दर अधिक पाई गई, जबकि सामान्यीकृत द्रव्यमान के घटने की दर कम पाई गई, जिसके परिणामस्वरूप कार्बन मोनोऑक्साइड उत्सर्जन में कमी देखी गई। मूंगफली के छिलकों से बने पेलेट का व्यवहार अपेक्षाकृत कम अनुकूल दिखा क्योंकि उन्हें बार-बार पुनः प्रज्वलित करने की आवश्यकता पड़ी।

तीसरे चरण में बाजार से खरीदे गए पेलेटों का दहन टॉप-लिट अपड्राफ्ट चूल्हे में किया गया। इस दौरान ईंधन के फिक्स्ड-बेड का द्रव्यमान, चूल्हे के निकास पर लौ का तापमान, तथा कार्बन मोनोऑक्साइड और कणीय पदार्थों के उत्सर्जन को वास्तविक समय में मापा गया। प्राप्त आंकड़ों का विश्लेषण करके पेलेट व्यास, लंबाई और बायोमास प्रकार का पेलेट के ज्वाला के साथ तथा उसके बाद लकड़ी से बने हुए कोयले के जलने की दर पर प्रभाव निर्धारित किया गया।

एकल पेलेट प्रयोगों के आधार पर टॉप लिट अपड्राफ्ट फिक्स्ड-बेड चूल्हे के प्रारूप में दहन दर का अनुमान लगाने की एक कार्यप्रणाली भी प्रस्तावित की गई, जिससे उत्साहजनक परिणाम मिले। इस विधि को अधिक विस्तृत आँकड़ों व प्रासंगिक मापदंडों के साथ और अधिक परिष्कृत किया जा सकता है।

इसके अतिरिक्त, फिक्स्ड-बेड में पेलेटों को शीघ्र प्रज्वलित करने के लिए बुरादा और मोमबत्ती के मोम से बने इग्निशन पेलेट भी विकसित किए गए। ये पेलेट लगभग एक सेकंड में प्रज्वलित हो जाते हैं और फिक्स्ड-बेड में पेलेटों के प्रभावी प्रज्वलन के लिए पर्याप्त समय तक जलते रहते हैं।

अंततः, उपलब्ध संख्यात्मक कोड का उपयोग करके टॉप लिट अपड्राफ्ट मोड में पेलेटों के फिक्स्ड-बेड में दहन के लिए सिमुलेशन परिणाम भी प्रस्तुत किए गए हैं।

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Nomenclatures

Abbreviations

ARB	As-received basis
ASTM	American Society for Testing and Materials
C	Carbon
C_PI	Commercial pine residues
C_PO	Commercial poplar residues
C_SD	Commercial sawdust residues
DAF	Dry-ash-free basis
DB	Dry basis
DTG	Derivative thermogravimetric
H	hydrogen
In_GS	In-house groundnut shell residues
In_MW	In-house mustard wastes residues
In_SD	In-house sawdust residues
ISO	International Organization for Standardization
N	Nitrogen
O	Oxygen
S	Sulphur
TGA	Thermogravimetric Analysis
TLUD	Top-Lit Up Draught
UTM	Universal Testing Machine

Greek Letters

ρ	Density (kg/m ³)
γ	Char yield (kg/kg)
ϵ	Void fraction (-)

Symbols

D	Diameter of combustion chamber (mm)
HHV	Higher heating value (MJ/kg)
L	Length of the combustion chamber (mm)
LHV	Lower heating value (MJ/kg)
VM	Volatile matter on dry-ash free basis (% wt.)

Subscripts

*	Dry-ash-free basis
b	Pellet bed
f	Fluid
p	Pellet
s	Solid