

DEVELOPMENT OF BIOMASS PELLET BASED CLEAN COOKSTOVE FOR COOKING/HEATING APPLICATIONS

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Development of Biomass Pellet Based Clean Cookstove for Cooking/Heating Applications

by

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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

July 2023

DEDICATED
TO
MY BELOVED PARENTS

DECLARATION

I hereby declare that the work presented here in the thesis entitled “Development of Biomass Pellet Based Clean Cookstove for Cooking/Heating Applications” has been carried out by me towards the partial fulfilment of the requirement for the award of the degree of Doctor of Philosophy at the Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The content 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 by me.

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CERTIFICATE

This is to certify that the thesis entitled “**Development of Biomass Pellet Based Clean Cookstove for Cooking/Heating Applications**” being submitted by **Mr. Himanshu** in fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work performed by him under our joint guidance and supervision at **Department of Energy Science and Engineering, Indian Institute of Technology Delhi.**

Further, the results obtained herein have not been submitted in part or in full to any other University or Institute for the award of any degree to the best of our knowledge.



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ABSTRACT

More than 2.6 billion people across the globe do not have access to clean cooking facilities and still rely on traditional open fired cookstoves to fulfil their cooking energy needs. These traditional cookstoves are responsible for emissions of harmful pollutants into the environment deteriorating the human health and environment. Gasifier based cookstoves are an attractive option in comparison to traditional cookstoves as they offer higher efficiency, less smoke, uniform flame, flexibility to vary power output, and do not require continuous attention of the user during the operation. This study presents the development and optimization of biomass pellet based clean cookstove for cooking/heating applications. The experimental testing facilities have been established to investigate the thermal performance and emission characteristics of any cookstove. The comparative performance evaluation of five different cookstove models, including three forced draft cookstoves named as FD 1.1, FD 1.2, and FD 1.3, developed in the laboratory; a traditional cookstove; and LPG stove have been carried out under the same laboratory conditions. Further, the annual fuel savings and emission reduction potentials of these gasifier models have been estimated with respect to the baseline (traditional) stove.

An extensive literature survey highlights a huge variation in performance parameters among different cookstove models. Therefore, concept of star rating has been proposed in this study to accommodate all the performance parameters of a cookstove model into a single parameter based on the importance of each viz. $PM_{2.5}$, CO and thermal efficiency. The performance of the developed forced draft cookstove models viz. FD 1.1, FD 1.2, and FD 1.3 have been compared with the traditional, LPG and other MNRE approved cookstove models tested under similar operating conditions using star rating. It is found that FD 1.3 cookstove model is 3 star, while FD 1.1 and FD 1.2 cookstove models are in the category of 4 star, while

all other MNRE approved cookstoves ranged between 1 star and 3 star. Further, FD 1.2 cookstove model is found to be superior as compared to those of FD 1.1 and FD 1.3 models on the basis of the proposed star rating.

A two-dimensional axisymmetric computational fluid dynamics (CFD) model of the developed cookstove FD 1.2 has been created in ANSYS Fluent to analyze the fluid flow, temperature distribution, and the heat loss from different parts of the cookstove. The primary governing equations of continuity, momentum, and energy, and different models used to simulate phenomenon such as combustion, turbulence, and heat transfer have been presented. Grid independent test has been carried out by varying the mesh size to ensure the accuracy of computational results. Furthermore, the computational results have been validated with the experimental results acquired from the testing of the developed model FD 1.2. The simulation results indicated that the heat loss from the combustion chamber to the outer wall is predominant via conduction through the top plate of the cookstove and radiation from the outer wall of the combustion chamber as compared to the convection through preheated secondary air in the annulus chamber.

Thermal imaging test of FD 1.2 cookstove has also been carried out, and the outer surface temperature of the cookstove is found to be significantly higher than the permissible limit of 60 °C as prescribed by Bureau of Indian Standards. The thickness of insulation required to minimize the heat losses from the developed model has also been optimized and the influence of primary and secondary airflow rates on the performance of the final prototype has been investigated. Further, the effect of varying secondary airflow rates on the thermal efficiency and emissions of CO, NO and PM_{2.5} at three different primary airflow rates has been analyzed. The performance of the final prototype has also been compared with the initially developed model, a traditional cookstove and an LPG stove. The emission factor of PM_{2.5} and CO

emissions from the developed final prototype is found to be four times and ten times lower as compared to the gold standard LPG stove, respectively.

The experimental results indicated that the pattern of secondary air introduction into the cookstove significantly affects the thermal efficiency and emission characteristics of gasifier models using processed biomass fuel. It has been observed that the uniform distribution of secondary air into the combustion chamber results in better mixing of air with the volatiles, leading to better emission characteristics. The thermal efficiency is found to be decreasing gradually with an increase in secondary airflow rate at each primary airflow rate. The emissions of CO and PM_{2.5} first decrease and, thereafter, increase with an increment in secondary airflow rate for each primary airflow rate. However, the emissions of NO first increase, attain maximum value and, thereafter, decline with increase in secondary airflow rate. The emissions of CO and PM_{2.5} are higher at both low and high values of secondary airflow rates. Therefore, an optimum secondary airflow rate exists, corresponding to the least emissions at each value of the primary airflow rate. The primary to secondary air ratio of 2:3 resulted in the lowest emissions of CO at different primary airflow rates.

दुनिया भर में 2.6 अरब से अधिक लोगों के पास स्वच्छ खाना पकाने की सुविधाएं नहीं हैं और वे अभी भी अपनी खाना पकाने की ऊर्जा जरूरतों को पूरा करने के लिए पारंपरिक चूल्हों पर निर्भर हैं। ये पारंपरिक चूल्हे पर्यावरण में हानिकारक प्रदूषकों के उत्सर्जन के लिए जिम्मेदार हैं जो मानव स्वास्थ्य और पर्यावरण को खराब कर रहे हैं। गैसीफायर आधारित चूल्हे पारंपरिक चूल्हों की तुलना में एक आकर्षक विकल्प हैं, क्योंकि वे उच्च दक्षता, कम धुआं, समान लौ, अलग-अलग शक्ति उत्पादन के लिए लचीलापन प्रदान करते हैं, और इनके संचालन के दौरान उपयोगकर्ता के निरंतर ध्यान की आवश्यकता नहीं होती है। यह अध्ययन खाना पकाने/तापक अनुप्रयोगों के लिए बायोमास पेलेट आधारित स्वच्छ चूल्हे के विकास और अनुकूलन को प्रस्तुत करता है। किसी भी चूल्हे के ऊष्मीय प्रदर्शन और उत्सर्जन विशेषताओं की जांच के लिए प्रायोगिक परीक्षण सुविधाएं स्थापित की गई हैं। प्रयोगशाला में विकसित एफडी 1.1, एफडी 1.2 और एफडी 1.3 नाम के तीन प्रणोदित झोंक चूल्हे, एक पारंपरिक चूल्हे, और एलपीजी चूल्हे सहित पांच अलग-अलग चूल्हों का तुलनात्मक प्रदर्शन मूल्यांकन समान प्रयोगशाला स्थितियों के तहत किया गया है। इसके अतिरिक्त, आधारभूत (पारंपरिक) चूल्हे के संबंध में इन गैसीफायर मॉडल की वार्षिक ईंधन बचत और उत्सर्जन में कमी की क्षमता का अनुमान लगाया गया है।

एक व्यापक साहित्य सर्वेक्षण विभिन्न चूल्हों के बीच प्रदर्शन मापदंडों में भारी भिन्नता पर प्रकाश डालता है। इसलिए, प्रत्येक के महत्व के आधार पर चूल्हों के सभी प्रदर्शन मापदंडों जैसे कार्बन मोनोआक्साइड, पीएम_{2.5} (परटीकुलेट मैटर) और ऊष्मीय दक्षता को एक ही मापदंड में समायोजित करने के लिए इस अध्ययन में स्टार रेटिंग की अवधारणा प्रस्तावित की गई है। । विकसित प्रणोदित झोंक चूल्हों एफडी 1.1, एफडी 1.2, और एफडी 1.3 के प्रदर्शन की तुलना स्टार रेटिंग का उपयोग करके समान परिचालन स्थितियों के तहत परीक्षण किए गए पारंपरिक, एलपीजी और अन्य एमएनआरई अनुमोदित चूल्हों के साथ की गई है। यह पाया गया है कि एफडी 1.3 चूल्हा 3 स्टार है, जबकि एफडी 1.1 और एफडी 1.2 चूल्हे 4 स्टार की

श्रेणी में हैं, जबकि अन्य सभी एमएनआरई अनुमोदित चूल्हे 1 स्टार और 3 स्टार के बीच हैं। इसके अतिरिक्त प्रस्तावित स्टार रेटिंग के आधार पर एफडी 1.2 चूल्हा एफडी 1.1 और एफडी 1.3 चूल्हों की तुलना में बेहतर पाया गया है।

चूल्हे के विभिन्न हिस्सों से द्रव प्रवाह, तापमान वितरण और गर्मी के नुकसान का विश्लेषण करने के लिए एनसिस फ्लुएंट में विकसित एफडी 1.2 चूल्हे का एक द्वि-आयामी अक्षीय कम्प्यूटेशनल तरल गतिशीलता (सीएफडी) मॉडल बनाया गया है। निरंतरता, संवेग और ऊर्जा के प्राथमिक नियामक समीकरण और दहन, विक्षोभ और ऊष्मा हस्तांतरण जैसी घटनाओं का अनुकरण करने के लिए उपयोग किए जाने वाले विभिन्न मॉडल प्रस्तुत किए गए हैं। कम्प्यूटेशनल परिणामों की सटीकता सुनिश्चित करने के लिए जाल के आकार को अलग करके ग्रिड स्वतंत्र परीक्षण किया गया है। इसके अलावा, कम्प्यूटेशनल परिणामों को विकसित एफडी 1.2 चूल्हे के परीक्षण से प्राप्त प्रयोगात्मक परिणामों के साथ मान्य किया गया है। अनुकरण परिणामों से संकेत मिलता है कि दहन कक्ष से बाहरी दीवार तक का ऊष्म हस्तांतरण, वलय कक्ष में पहले से गरम द्वितीयक हवा के माध्यम से संवहन की तुलना में, चूल्हे की शीर्ष प्लेट और दहन कक्ष की बाहरी दीवार से विकिरण के माध्यम से प्रमुख है।

एफडी 1.2 चूल्हे का ऊष्मीय इमेजिंग परीक्षण भी किया गया है, और चूल्हे की बाहरी सतह का तापमान भारतीय मानक ब्यूरो द्वारा निर्धारित 60 डिग्री सेल्सियस की अनुमेय सीमा से काफी अधिक पाया गया है। विकसित चूल्हे से ताप हानि को कम करने के लिए आवश्यक इन्सुलेशन की मोटाई को भी अनुकूलित किया गया है और अंतिम प्रोटोटाइप के प्रदर्शन पर प्राथमिक और द्वितीयक वायु प्रवाह दरों के प्रभाव की जांच की गई है। इसके अलावा, तीन अलग-अलग प्राथमिक वायु प्रवाह दरों पर कार्बन मोनोआक्साइड, नाइट्रिक ऑक्साइड और पीएम_{2.5} की ऊष्मीय दक्षता और उत्सर्जन पर अलग-अलग माध्यमिक वायु प्रवाह दरों के प्रभाव का विश्लेषण किया गया है। अंतिम प्रोटोटाइप के प्रदर्शन की तुलना प्रारंभिक रूप से विकसित मॉडल, एक पारंपरिक कुकस्टोव और एक एलपीजी स्टोव से भी की गई है। विकसित अंतिम

प्रोटोटाइप से पीएम_{2.5} और कार्बन मोनोआक्साइड का उत्सर्जन कारक स्वर्ण मानक एलपीजी चूल्हे की तुलना में क्रमशः चार गुना और दस गुना कम पाया गया है।

प्रायोगिक परिणामों से संकेत मिलता है कि चूल्हे में द्वितीयक वायु परिचय का स्वरूप संसाधित बायोमास ईंधन का उपयोग करने वाले गैसीफायर मॉडल की ऊष्मीय दक्षता और उत्सर्जन विशेषताओं को महत्वपूर्ण रूप से प्रभावित करता है। यह देखा गया है कि दहन कक्ष में द्वितीयक वायु के समान वितरण के परिणामस्वरूप वाष्पशील पदार्थों के साथ वायु का बेहतर मिश्रण होता है, जिससे बेहतर उत्सर्जन विशेषताएँ प्राप्त होती हैं। प्रत्येक प्राथमिक वायुप्रवाह दर पर द्वितीयक वायुप्रवाह दर में वृद्धि के साथ द्वितीयक दक्षता धीरे-धीरे कम होती पाई गई है। प्रत्येक प्राथमिक वायु प्रवाह दर पर द्वितीयक वायु प्रवाह दर में वृद्धि के साथ कार्बन मोनोआक्साइड और पीएम_{2.5} का उत्सर्जन पहले कम होता है और उसके बाद बढ़ता है। हालाँकि, नाइट्रिक ऑक्साइड का उत्सर्जन पहले बढ़ता है, अधिकतम मूल्य प्राप्त करता है और उसके बाद, द्वितीयक वायुप्रवाह दर में वृद्धि के साथ गिरावट आती है। कार्बन मोनोआक्साइड और पीएम_{2.5} का उत्सर्जन द्वितीयक वायुप्रवाह दर के निम्न और उच्च दोनों मूल्यों पर अधिक है। इसलिए, प्राथमिक वायु प्रवाह दर के प्रत्येक मूल्य पर न्यूनतम उत्सर्जन के अनुरूप एक इष्टतम माध्यमिक वायु प्रवाह दर मौजूद है। 2:3 के प्राथमिक से द्वितीयक वायु अनुपात के परिणामस्वरूप विभिन्न प्राथमिक वायुप्रवाह दरों पर कार्बन मोनोआक्साइड का सबसे कम उत्सर्जन पाया गया है।

CONTENTS

Declaration		i
Certificate		iii
Acknowledgements		v
Abstract		vii
Contents		xi
List of Figures		xv
List of Tables		xix
Nomenclature		xxi
Chapter 1	Introduction	1
	1.1 Background	1
	1.2 Motivation for present study	8
	1.3 Organization of the thesis	9
Chapter 2	Literature Review	13
	2.1 Introduction	13
	2.2 Evolution of cookstoves	13
	2.3 Classification of biomass cookstoves	15
	2.3.1 Technology	15
	2.3.2 Combustion	18
	2.3.3 Application	19
	2.3.4 Draft	19
	2.3.5 Chimney	20
	2.3.6 Material of construction	21
	2.3.7 Portability	23
	2.3.8 Fuel	24
	2.4 Cookstove programs in India	24
	2.5 Technological advancements	33
	2.5.1 Material of construction	34
	2.5.2 Mode of air supply	34
	2.5.3 Skirt	35

	2.5.4 Insulation	35
	2.5.5 Grate	36
	2.5.6 Damper	36
	2.5.7 Baffle	37
	2.5.8 Thermoelectric generators	37
	2.5.9 Gasifier Stoves	38
	2.5.10 Computational modelling	44
	2.6 Testing Protocols	47
	2.6.1 Laboratory tests	48
	2.6.2 Field tests	50
	2.6.3 Miscellaneous tests	52
	2.7 Research gaps	53
	2.8 Objectives of the present research	54
Chapter 3	Experimental Testing Facility and Methodology	55
	3.1 Introduction	55
	3.2 Testing facility and methodology	55
	3.2.1 Thermal efficiency	58
	3.2.2 CO emission	60
	3.2.3 PM _{2.5} emission	61
	3.2.4 Energy and exergy analysis	63
	3.3 Biomass characterization	65
	3.3.1 Proximate analysis	65
	3.3.2 Ultimate analysis	68
	3.3.3 Calorific value	69
	3.3.4 Thermogravimetric analysis	70
Chapter 4	Development of Improved Cookstoves and Their Comparison with Existing Cookstoves	71
	4.1 Introduction	71
	4.2 Design methodology	73
	4.2.1 Power output	73
	4.2.2 Fuel consumption rate	73
	4.2.3 Combustion chamber diameter	74
	4.2.4 Height	74

	4.2.5 Air flow rate	75
	4.3 Cookstove models developed in the present study	75
	4.4 Uncertainty analysis	76
	4.5 Performance evaluation of different models	77
	4.5.1 Fuel characteristics	77
	4.5.2 Power output and burning rate	78
	4.5.3 Energy and exergy efficiency	79
	4.5.4 Emission of CO and PM _{2.5}	84
	4.6 Performance comparison	85
	4.6.1 Rankings of various cookstove models	87
	4.6.2 Star rating	90
	4.7 Estimation of annual emissions	93
	4.8 Fuel savings and emission reduction potentials	94
	4.9 Concluding remarks	96
Chapter 5	Heat Loss Estimation Using CFD Approach	99
	5.1 Introduction	99
	5.2 Developed forced draft cookstove model (FD 1.2)	100
	5.3 Computational modelling	101
	5.3.1 Mathematical model	102
	5.3.2 Boundary conditions	104
	5.3.3 Grid independency test	104
	5.3.4 Model validation	105
	5.4 Variation of CO and combustion zone temperature	106
	5.5 Fluid flow and temperature distribution	109
	5.6 Variation of temperature and heat flux	110
	5.7 Energy flow diagram	111
	5.8 Effect of insulation over FD 1.2 model	112
	5.9 Performance comparison with other models	113
	5.10 Emission reduction potential	116
	5.11 Concluding remarks	119
Chapter 6	Prototype Development With Optimized Insulation and Airflow Rates	121
	6.1 Introduction	121

6.2 Thermal imaging test	121
6.3 Optimum thickness of insulation	122
6.4 Optimization of airflow rates	125
6.4.1 Effect of airflow rates on fuel consumption	126
6.4.2 Effect of airflow rates on power output	127
6.4.3 Effect of airflow rates on thermal efficiency	128
6.4.4 Effect of airflow rates on CO emission	130
6.4.5 Effect of airflow rates on PM _{2.5} emission	131
6.4.6 Effect of airflow rates on NO emission	132
6.4.7 Effect of airflow rates on combustion zone temperature	133
6.4.8 Optimum emissions of CO and PM _{2.5} at different primary airflow rates	136
6.5 Final prototype	137
6.5.1 Comparison of annual cooking requirement per household	138
6.6 Concluding remarks	139
Chapter 7 Overall Conclusions and Recommendations	141
7.1 Overall conclusions	141
7.2 Limitations of present work	145
7.3 Recommendations for future work	146
References	149
List of Publications	167
About the Author	169

LIST OF FIGURES

Figure 1.1	Schematic of a forced draft gasifier stove	7
Figure 2.1	Classification of biomass cookstove	15
Figure 2.2	A pictorial view of (a) three stone fire (TSF) stove and (b) mud stove (CCA, 2022; Baqir et al. 2019)	16
Figure 2.3	Classification of cookstove testing protocols (Sutar et al., 2015; Arora and Jain, 2016)	48
Figure 3.1	Schematic diagram of experimental testing facility	56
Figure 3.2	Pictorial view of experimental testing facility	57
Figure 3.3	Energy flow diagram for cookstove	63
Figure 3.4	Exergy flow diagram for cookstove	64
Figure 3.5	Pictorial view of (a) hot air oven and (b) muffle furnace	67
Figure 3.6	Pictorial view of CHNS analyzer	69
Figure 3.7	Pictorial view of bomb calorimeter	70
Figure 4.1	Line diagram of forced draft gasifier model cookstoves	76
Figure 4.2	TGA-DTA curve for biomass pellets used in the study	78
Figure 4.3	Burning rate and power output of different cookstove models	79
Figure 4.4	Variation of energy efficiency of different cookstove models with time	80
Figure 4.5	Variation of exergy efficiency of different cookstove models with time	81
Figure 4.6	Average energy and exergy efficiency of different cookstove models	82
Figure 4.7	Emission of (a) CO and (b) PM _{2.5} per megajoule of energy delivered (MJ _D) for different cookstove models	84
Figure 4.8	Thermal efficiency rankings of developed cookstoves w.r.t other cookstoves	88
Figure 4.9	CO emission rankings of developed cookstoves w.r.t other cookstoves	88
Figure 4.10	PM _{2.5} emission rankings of developed cookstoves w.r.t other cookstoves	89

Figure 4.11	The weighted score and star rating of different cookstove models	92
Figure 4.12	Annual (a) Fuel and CO ₂ savings and (b) Emission reduction potential of PM _{2.5} and CO from forced draft cookstove models	95
Figure 5.1	Schematic diagram of developed cookstove model (FD 1.2)	100
Figure 5.2	A 2D axisymmetric computational model	102
Figure 5.3	Variation of wall heat flux on the bottom of the vessel	105
Figure 5.4	Variation of outer wall temperature with height of cookstove	106
Figure 5.5	Variation of combustion zone temperature and CO concentration during the cookstove operation	107
Figure 5.6	Contours of (a) Velocity and (b) Temperature distribution in the computational domain	109
Figure 5.7	Variation of temperature and heat flux over the outermost wall	111
Figure 5.8	Estimation of heat loss from forced draft cookstove	112
Figure 5.9	Comparison of thermal efficiency and emissions of CO and PM _{2.5} from FD 1.2 and FD 1.2M cookstove models	113
Figure 5.10	Comparison of (a) Thermal efficiency and (b) Emissions of CO and PM _{2.5} from FD 1.2 and FD 1.2M cookstove models with other forced draft pellet based cookstoves	115
Figure 5.11	Comparison of (a) Annual emissions of CO and (b) PM _{2.5} from traditional, FD 1.2 and FD 1.2M cookstoves and annual emission reduction potentials of (c) CO and (d) PM _{2.5} from FD 1.2 and FD 1.2M cookstove models	118
Figure 6.1	Photographic view of the advanced biomass cookstove during experiment (a) at the beginning of the experiment and (b) towards the completion of the experiment using thermal imaging camera FLIR A325sc	122
Figure 6.2	Variation of percentage reduction in heat loss w.r.t insulation thickness	124
Figure 6.3	A schematic of developed final prototype	124
Figure 6.4	Fuel consumption vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	127

Figure 6.5	Power output vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	128
Figure 6.6	Thermal efficiency vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	129
Figure 6.7	CO emission vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	130
Figure 6.8	PM _{2.5} emission vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	132
Figure 6.9	NO emission vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	133
Figure 6.10	Combustion zone temperature vs secondary airflow rate for different values of primary airflow rates viz. (a) 0.003 kg/s, (b) 0.004 kg/s, and (c) 0.005 kg/s	135
Figure 6.11	Variation of optimized emissions of CO and PM _{2.5} at different primary airflow rates	136
Figure 6.12	Comparison of CO and PM _{2.5} emission factors of developed final prototype with traditional and LPG cookstoves	137
Figure 6.13	Annual emissions of CO and PM _{2.5} per household from developed cookstove w.r.t traditional and LPG stoves	138

LIST OF TABLES

Table 2.1	List of some improved cookstove models developed during NPIC in India (MNES, 1993)	25
Table 2.2	List of MNRE approved natural and forced draft cookstoves (MNRE, 2018)	31
Table 2.3	Performance comparison of gasifier cookstove models (CCA, 2022)	40
Table 3.1	Resolution of real time measurements of gaseous pollutants	61
Table 4.1	Performance and emission characteristics of different cookstoves (MNRE, 2018)	86
Table 4.2	Emission factors and annual emissions from different cookstove models	94
Table 6.1	Composition of pellets used in this study	125
Table 6.2	Different airflow rate configurations used in the present study	126

NOMENCLATURE

A	Mass of filter paper before deposition (mg)
a_s	Characteristic strain rate
B	Mass of filter paper after deposition (mg)
c	Reaction progress variable
C	Total volume of gases passed through sampler in an hour (L)
c_1	Net heating value of fuel (kJ/kg)
c_2	Net heating value of oil (kJ/kg)
CO	Carbon monoxide
CO ₂	Carbon dioxide
C_p	Average specific heat of mixture at constant pressure (kJ/kg-K)
C_i	Species specific heat for i^{th} iteration
C_v	Specific heat of vessel (J/kg-K)
C_w	Specific heat of water (J/kg-K)
D	Diameter of stove (m)
EF_i	Emission factor of species i (g/kg)
erfc^{-1}	Inverse complementary error function
f	Mixture fraction space
H	Height of stove (m)
H_d	Total heat delivered to the cooking vessel (MJ _D)
h_i	Specific enthalpy for i^{th} species (kJ/kg)
h_o	Convective heat transfer coefficient (W/m ² -K)
K	Laminar thermal conductivity of mixture (W/m-K)
K_i	Thermal conductivity of insulation layer (W/m-K)
K_o	Thermal conductivity of mild steel (W/m-K)
M_f	Mass of fuel burnt (kg)
M_i	Mass of emitted species i (g)
m_v	Mass of vessel (kg)
m_w	Mass of water in the vessel (kg)

n	Total number of vessels utilized in the experiment
NO	Nitrogen oxide
Nu_L	Average Nusselt number for characteristic length L
O ₂	Oxygen
G	Concentration of CO in the diluted exhaust gas (ppm)
P	Joint probability density function (PDF) of reaction progress
Pr	Prandtl number
Q	Volume of exhaust gases passing through duct in an hour (L/h)
Q _n	Power output (kW)
r	Radius of cookstove up to insulation layer (m)
Ra_L	Rayleigh number for characteristic length L
r _i	Radius of the cookstove without insulation (m)
r _o	Radius of the outermost layer of the cookstove with insulation (m)
Sc _t	Turbulent Schmidt number
$\overline{S_{Yc}}$	Mean source term
SFR	Finite rate flamelet source term
S _i	Species reaction rate for i th species
T	Absolute temperature of the sampled gas fed to the analyzer (K)
T	Temperature (K)
t	Time required for operation of cookstove (h)
T ₁	Initial temperature of the water (K)
T ₂	Final temperature of water before changing the vessel (K)
T ₃	Final temperature of the water in the last pot (K)
T _a	Ambient temperature (K)
T _f	Temperature of the fuel being burnt in the combustion chamber (K)
T _{fv}	Final temperature of vessel (K)
T _{fw}	Final temperature of water (K)
T _{iv}	Initial temperature of vessel (K)
T _{iw}	Initial temperature of water (K)
T _o	Temperature of surroundings (K)

T_s	Average temperature of the outer wall without insulation (K)
$u_1, u_2, u_3, \dots, u_n$	Uncertainties in $z_1, z_2, z_3, \dots, z_n$
V	Volume of exhaust gases (L)
U_o	Initial mass of sample (g)
U_f	Final mass of sample (g)
W	Mass of the empty vessel along with the lid (kg)
w	Mass of water filled in the vessel (kg)
W_1	Mass of fuel and cookstove measured before burning (kg)
W_2	Mass of fuel and cookstove measured after half an hour of burning (kg)
x	Volume of oil used (ml)
X	Burning rate of the cookstove (kg/h)
X_d	Weight of sample after drying
X_o	Weight of wet sample
Y	Function
Y_i	Mass fraction for i^{th} species
Z	Amount of $PM_{2.5}$ per litre of sample passed through sampler (mg/L)
$z_1, z_2, z_3, \dots, z_n$	Independent variables

Greek symbols

η	Thermal efficiency of cookstove
Ψ	Exergy efficiency of cookstove
ρ_f	Density of fuel (kg/m^3)
ρ_a	Density of air (kg/m^3)
ρ_o	Density of oil (g/cm^3)
ε	Equivalence ratio
ρ_∞	Density of oxidizer stream (kg/m^3)
μ_t	Turbulent viscosity of mixture (Pa-s)

Abbreviations

AR	Agricultural residue
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ARC	Aprovecho Research Centre
BCT	Burning cycle test
BIS	Bureau of Indian Standards
CCT	Controlled cooking test
CDT	Cookstove durability test
CFD	Computational fluid dynamics
DTA	Differential thermal analysis
EC	Elemental carbon
FCR	Fuel consumption rate (kg/h)
FGM	Flamelet generated manifold
GACC	Global Alliance for Clean Cookstoves
GHGs	Greenhouse gases
HAP	Household air pollution
HTP	Heterogeneous testing protocol
KPT	Kitchen performance test
LMICs	Low- and middle-income countries
LPG	Liquified petroleum gas
MC	Moisture content
MNRE	Ministry of New and Renewable Energy
NBIC	National biomass cookstove initiative
NPIC	National program on improved chulah
OC	Organic carbon
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate matter
SA	Stoichiometric air requirement
SGR	Specific gasification rate
SUMs	Stove use monitors
TBU	Technical Backup Unit
TCS	Traditional cookstove
TEG	Thermoelectric generator

TGA	Thermogravimetric analysis
TSF	Three stone fire
UCT	Uncontrolled cooking test
VFD	Variable frequency drive
WBT	Water boiling test