DEVELOPMENT OF GUIDELINES FOR DESIGN OF TLUD COOKSTOVES

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February 2024

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by

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submitted
in fulfillment of the requirements of the degree of
DOCTOR OF PHILOSOPHY
to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

February 2024

Dedicated to

My mother Mrs. Pushpa Pandey and father Mr. Binod Kumar Pandey,

and

To my wife Sruti, daughter Suvigya and son Praganaya

Certificate

This is to certify that the thesis entitled "**Development of Guidelines for Design of TLUD Cookstoves**" being submitted by **Mr. Vipul Vibhanshu** (2016MEZ8270) to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bona-fide research work carried out by him under our supervision. The candidate has fulfilled the requirements for the submission of this research work for his thesis. In our opinion, this thesis has attained the standard needed for the award of a Ph.D. degree of this institute. The results contained in this thesis have not been submitted, in part or in full, to any other university or institute for the award of any degree or diploma.

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Acknowledgments

एकमप्यक्षरं यस्तु गुरुः शिष्ये निवेदयेत् । पृथिव्यां नास्ति तद् द्रव्यं यद्दत्वा ह्यनृणी भवेत् ॥

If a Guru teaches even a single letter of the alphabet to a student, there is no such thing on this Earth, which, on being given to the Guru can render the student free from the debt of learning from his teacher.

The above shloka (spiritual poem) exactly resembles the quality of my Ph.D. Supervisors Prof. Sangeeta Kohli and Prof. M. R. Ravi. Prof. Sangeeta Kohli is a very sincere, knowledgeable, and kind-hearted personality. In my very first interaction with both, I decided to work with them because of their vision toward research. Their motivation to do work for the ground-level people and their upliftment make me fascinate and motivate me to work with them.

Prof. Sangeeta Kohli is a kind, soft-speaking, and studious personality. Prof. Kohli taught me hundreds of concepts like uncertainty analysis, molar conversions, programming, primary entrainment, fuel characterization *etc*. She always says, ‘If you are not knowing things, don’t worry, Ph. D. is a training process, we will teach you’. She consistently provided me valuable guidance, not only for my studies but also for my personal life, which helped me maintain a good outlook.

Prof. M. R. Ravi is an amicable, disciplined, and genius personality. My academic growth has been significantly influenced by his knowledge and guidance. My ability to think critically and solve problems has improved as a result of his mentoring, and I now feel more confident in taking on difficult research problems. His mentorship has not only broadened my intellectual horizons but has also instilled in me a sense of purpose and a lifelong love for learning.

Their collective mentoring has given me a strong foundation in my field of study and has shaped me into a more independent and critical thinker. Their constant support has been the anchor that has kept me afloat during this difficult journey, whether it was through countless hours of discussions, constructive criticism of my work, or gentle prodding during moments of self-doubt.

My deepest gratitude to the members of the student research committee – Prof. Anjan Ray, Prof. Prabal Talukdar, and Prof. K. K. Pant. Their valuable guidance and constructive feedback during

SRC presentations have played a vital role in shaping my research and enhancing my academic journey.

Special thanks to Prof. P. M. V. Subbarao, Prof. B. Premachandran, and Prof. K. K. Agarwal for their continuous support throughout this work.

Additionally, I would like to express my gratitude to the members of the Mechanical Engineering Department at IIT Delhi for their support at various levels during this entire journey.

I take immense pleasure in expressing my gratitude towards my senior, Dr. Abdul Rahman Khan, Dr. Vinod Kumar Yadav, Dr. Zeba Naaz, and Satendra Rana whose unwavering support and assistance were invaluable to my research endeavors. I am particularly thankful to my colleague, Thirmoorthy, who consistently displayed a keen interest in my progress and provided me with valuable suggestions and feedback whenever needed. My special thanks to Dr. Vikas Jangir and Dr. Anurag Mishra for their valuable support at various levels of my work.

I would like to express my gratitude to Mr. Manish Gupta for his assistance in one of our collaborated projects Ecosense Pvt. Ltd. I would also like to thank the combustion research lab in charge Mr. Vipin Kakkar and other lab mates Mr. Ankit Kumar, Mr. Mayank, Mrs. Reetu Bharti, and Mr. Vikas Kumar for their cooperation during this research work.

This acknowledgment would be incomplete without my gratitude toward our lab staff Mr. Badri Parsad Verma who made his presence in most of my experimental trials.

यं मातापितरौ क्लेशं सहेते सम्भवे नृणाम्। न तस्य निष्कृतिः शक्या कर्तुं वर्षशतैरपि॥

The trouble that the parents undergo in the birth of children, —for that there can be no compensation even in a hundred years.

I am immensely grateful to my dear parents, Ms. Pushpa Pandey, and Mr. Binod Pandey for their boundless affection, unwavering support, nurturing, and selfless efforts in providing me with education and shaping my path for the times ahead. I extend my heartfelt appreciation to my beloved spouse, Ms. Sruti, my very sweet daughter Suvigya and son Praganya for their affection, understanding, sacrifices, and unwavering support throughout the completion of this research endeavor. Her constant encouragement has been instrumental in my journey. I express my gratitude to my younger brother, Mr. Nipun Nikunj, for his continuous financial support, motivation, and encouragement. Additionally, I would like to extend my appreciation to my sister-in-law, Ms. Bandana, and Ms. Shikha for their assistance and kindness. Their unwavering support has been invaluable to me.

I would like to extend my gratitude to my in-laws, Mr. Vijay Kishor Singh, and brother-in-law Vinit. Their kindness and warmth have made me feel at home from the very beginning. I am deeply grateful for the love and care they have shown me, not only as their son-in-law but as a part of the family. I would like to express my appreciation to the entire extended family for their encouragement and belief in my abilities. Their continuous support has been instrumental in keeping me focused on my goals, and I am grateful for the positive energy they have brought into my life.

I am filled with profound gratitude as I extend my heartfelt appreciation to Mr. Amardeep, Mr. Ashish Singh, Mr. Jitendra Singh, and Mr. Vivek Kumar Verma. Their unwavering support, dedication, and camaraderie have made a significant impact on both my personal and professional journey. Their constant encouragement and belief in my abilities have been a driving force in overcoming challenges and achieving success. I am truly fortunate to have such incredible individuals in my life, as they have not only been exceptional colleagues but also genuine friends.

In the end, I would like to thank all those who helped me directly or indirectly during my Ph.D. duration. I would like to thank all those people who made this thesis possible and an unforgettable experience for me.

Abstract

Top Lit Updraft (TLUD) gasifier cookstoves have a high potential to reduce emissions in rural kitchens due to much cleaner combustion in these stoves as compared to traditional as well as improved combustion cookstoves. These stoves also result in high thermal efficiency. Although this type of cookstoves have been in existence for three decades now, literature on systematic design of such gasifier cookstoves is still scarce. This work aims at bridging this gap by evolving design recommendations for such cookstoves through a combination of experimental and numerical analysis of commercially available TLUD cookstoves.

The present work is divided into four phases: i) The disassembly of commercially available forced draft TLUD cookstoves to study their constructional features; ii) Understanding the airflow and distribution into primary and secondary air streams through matching of fan and system resistance characteristics using a combination of experiments and theoretical analysis of the fluid flow system of a TLUD cookstove; iii) Experimental interventions in commercial TLUD cookstoves, and parametric analysis of the effect of operating parameters on performance and emissions of TLUD cookstoves; iv) Numerical simulation of gasification in a TLUD cookstove using a 1-D model, to predict the burning rate, air to fuel ratio, cold and hot flow gasification efficiency and exit gas composition, and thus understand the influence of design and operating parameters on gasifier performance. Based on the learnings from these four activities, the present work would attempt to propose design guidelines for TLUD gasifier cookstoves.

In this study 10 cookstoves available in-house have been studied to get the information about their constructional features. Among these, 3 cookstoves (STOVE 1, STOVE 2 and STOVE 3) have been selected for detailed study of their construction, in terms of the air flow path and the arrangement and types of fans used, material and construction of combustion chamber, insulations and supporting frame for vessel.

A test rig has been prepared to determine the fan characteristics. Three fans available in the market were selected and tested at three different operating voltages of 6 V, 9 V and 12 V. Using this test rig, the head – discharge characteristics of these fans have been obtained. A separate test rig has also been prepared to determine the flow resistance characteristics of the cookstove system. By

matching the fan and system resistance characteristics, the operating points range has been determined for STOVE1 and STOVE2. The experimental results suggest that these types of cookstoves can efficiently operate even with low power requirements. The results also provide insights into which kind of flow passages show low flow resistance and which ones offer higher pressure drops – a useful insight for design of combustion airflow systems in TLUD cookstoves. In order to determine the flow distribution between primary and secondary air passages, an analytical model has been developed. Using this model, it was found that STOVE 1 has a primary - secondary air break-up in the range of 18%-82% to 22%-78% over its entire range of operating airflow rates. For STOVE 2 the primary to secondary air distribution is about 30-70% at all flow rates.

The experiments were conducted by varying the total air flow rate for STOVE 1 and STOVE 2. From the results, it emerges that when the primary airflow increases, the fuel burn rate also increases, and so does the air-biomass ratio – indicating that the rate at which fuel consumption increases is less than linear with increase in airflow rate. When the secondary air holes are closed and all air is supplied from primary air holes, burn rates increase more rapidly than when the total airflow is increased with secondary air holes open. This appears to be because the primary air helps in consuming char through oxidation as well, when more primary air is provided, and all products of pyrolysis and gasification burn outside the cookstove, with air from the atmosphere. Efficiency and maximum flame temperature improve as supply of primary air increases for a given total air. But beyond an optimal primary air flow, due to char consumption, the performance may deteriorate, indicating that there is an optimum around 28 – 35% of stoichiometric air as primary air. Use of burner plates to stabilize and regulate the flame improves flame temperatures and thermal efficiency owing to better mixing of secondary air with gasification products.

Numerical simulations of the gasification process in TLUD cookstove has been performed by developing a transient 1-D mathematical model of the phenomena in-house. The results obtained from the simulations are also compared with the experimental results and are found to be in reasonable agreement. Parametric study on the effect of fuel particle density, size and type and airflow rate was conducted. Simulation results show that the gas composition is relatively insensitive to fuel type, size and particle density. It was observed that at low particle density, char consumption rates determine biomass consumption rates, while at higher density, it is controlled by pyrolysis rates. Similarly, at larger particle size, biomass consumption rates are limited by the number of particles that can be present in the high temperature reaction area, while at smaller particle size, the consumption rate is determined by the total particle surface area. Increase in airflow rate shows a constant air-biomass ratio unlike experimentally observed. Keeping the superficial velocity constant, when the area of the reactor cross section is increased, the temperature and gas composition are unaltered and biomass consumption increases proportional to the increase in area – indicating a constant SGR. This appears to be the result of the model being 1-dimensional, since it is in variance with what is experimentally observed.

Making use of the observations and results of experimental and numerical analyses, a design approach has been evolved for the design of TLUD cookstoves. It is observed that unlike suggestions in the literature, the specific gasification rate SGR depends both on the cookstove height and the diameter, and on the superficial velocity, and dividing the fuel consumption rate by the area of the reactor does not completely eliminate the effect of the diameter. A more exhaustive and rigorous study is required to completely parametrize the influence of various cookstove design parameters on the SGR. Once SGR is available for a given gasifier – fuel combination, basic definitions of specific gasification rate and fuel consumption rate can be used to calculate the dimensions of the gasifier for a given requirement.

सार

टॉप लिट अपड्राफ्ट (TLUD) चूल्हों के द्वारा ग्रामीण रसोई में प्रदूषणको काफी कम किया जा सकता है क्योंकि इस चूल्हे में प्रदुषण कारक तत्व कम होते हैं और इन चूल्हों की दक्षता भी अधिक होती हैं। हालाँकि इस प्रकार के चूल्हे तीन दशकों से अस्तित्व में हैं, परंतु ऐसे गैसीफायर चूल्हों के व्यवस्थित डिजाइन पर साहित्य अभी भी दुर्लभ है। इस कार्य का उद्देश्य व्यावसायिक रूप से उपलब्ध TLUD चूल्हों के प्रयोगात्मक और संख्यात्मक विश्लेषण के संयोजन के माध्यम से TLUD चूल्हों के लिए डिजाइन सिफारिशों को विकसित करके इस अंतर को कम करना है ।

वर्तमान कार्य को चार चरणों में विभाजित किया गया है: i) व्यावसायिक रूप से उपलब्ध फ़ोर्सड्राफ्ट TLUD चूल्हों को पृथक करके उनकी रचनात्मक विशेषताओं का अध्ययन करना, ii) TLUD चूल्हों के द्रव प्रवाह प्रणाली के प्रयोगों और सैद्धांतिक विश्लेषण के संयोजन का उपयोग करके पंखे और सिस्टम प्रतिरोध विशेषताओं के मिलान के माध्यम से प्राथमिक और द्वितीयक वायु धाराओं में वायु प्रवाह और वितरण को समझना; iii) वाणिज्यिक TLUD चूल्हों में प्रायोगिक हस्तक्षेप, और TLUD चूल्हों के प्रदर्शन और उत्सर्जन पर ऑपरेटिंग मापदंडों के प्रभाव का पैरामीट्रिक विश्लेषण; iv) 1-आयामी मॉडल का उपयोग करके TLUD चूल्हों में गैसीकरण का संख्यात्मक अनुकरण, जलने की दर, हवा-ईंधन अनुपात, ठंडा और गर्म प्रवाह गैसीकरण दक्षता और निकास गैस संरचना की भविष्यवाणी कर इस प्रकार के गैसीफायर पर होने वाले डिजाइन और ऑपरेटिंग पैरामीटर के प्रभाव का अध्ययन। इन चार गतिविधियों से मिली सीख के आधार पर, वर्तमान कार्य में TLUD गैसीफायर चूल्हों के लिए डिज़ाइन दिशानिर्देश प्रस्तावित करने का प्रयास किया गया है ।

इस अध्ययन में घरेलू उपयोग में आने वाले व्यवसायिक रूप से उपलब्ध 10 चूल्हों का अध्ययन उनकी रचनात्मक विशेषताओं के बारे में जानकारी प्राप्त करने के लिए किया गया है। इनमें से, 3 चूल्हों (STOVE 1, STOVE 2 और STOVE 3) को उनके निर्माण के विस्तृत अध्ययन के लिए चुना गया है, जिसमें वायु प्रवाह पथ और इस्तेमाल किए गए पंखे की व्यवस्था और प्रकार, दहन कक्ष की सामग्री और निर्माण, इन्सुलेशन और सहायक फ्रेम शामिल हैं।

पंखे की विशेषताओं को निर्धारित करने के लिए एक परीक्षण रिग तैयार किया गया है। बाजार में उपलब्ध तीन पंखों का चयन किया गया और 6 V, 9 V और 12 V के तीन अलग-अलग ऑपरेटिंग वोल्टेज पर परीक्षण किया गया। इस टेस्ट्रिग का उपयोग करके, इन पंखों की हेड-डिस्चार्ज विशेषताएं प्राप्त की गई हैं। चूल्हों प्रणाली की प्रवाह प्रतिरोध विशेषताओं को निर्धारित करने के लिए एक अलग परीक्षण रिग भी तैयार किया गया है। पंखे और सिस्टम प्रतिरोध विशेषताओं का मिलान

करके, STOVE1 और STOVE2 के लिए ऑपरेटिंग पॉइंट रेंज निर्धारित की गई है। प्रायोगिक परिणाम बताते हैं कि इस प्रकार के चूल्हे कम बिजली की आवश्यकता के साथ भी कुशलतापूर्वक काम कर सकते हैं। परिणाम यह भी जानकारी प्रदान करते हैं कि किस प्रकार के प्रवाह मार्ग कम प्रवाह प्रतिरोध दिखाते हैं और कौन से उच्च दबाव ड्रॉप प्रदान करते हैं, यह TLUD चूल्हों में दहन वायु प्रवाह प्रणालियों के डिजाइन के लिए एक उपयोगी अंतर्दृष्टि स्थापित करता है। प्राथमिक और द्वितीयक वायु मार्ग के बीच प्रवाह वितरण निर्धारित करने के लिए, विश्लेषणात्मक मॉडल विकसित किया गया है। इस मॉडल का उपयोग करते हुए, यह पाया गया कि STOVE 1 का परिचालन एयरफ्लो दरों की पूरी श्रृंखला की तुलना में 18%-82% से 22%-78% की सीमा में एक प्राथमिक- द्वितीयक वायु का विभाजन है। STOVE 2 के लिए प्राथमिक से द्वितीयक वायु वितरण सभी प्रवाह दरों पर लगभग 30-70% है।

प्रयोग STOVE 1 और STOVE 2 के लिए कुल वायु प्रवाह दर को अलग-अलग करके किए गए थे। परिणामों से, यह उभर कर आता है कि जब प्राथमिक वायु प्रवाह बढ़ता है, तो ईंधन जलने की दर भी बढ़ जाती है, और वायु-बायोमास अनुपात भी बढ़ जाता है जो की यह दर्शाता है कि दर जिस पर वायु प्रवाह दर में वृद्धि के साथ ईंधन की खपत रैखिक से कम होती है। जब द्वितीयक वायु छिद्र बंद हो जाते हैं और सभी वायु को प्राथमिक वायु छिद्रों से आपूर्ति की जाती है, तो जलने की दर उस समय की तुलना में अधिक तेजी से बढ़ती है जबकि द्वितीयक वायु छिद्र खुले होने पर कुल वायु प्रवाह बढ़ जाता है। ऐसा प्रतीत होता है कि प्राथमिक वायु ऑक्सीकरण के माध्यम से चार का उपभोग करने में भी मदद करती है, जब अधिक प्राथमिक वायु प्रदान की जाती है तो पायरोलिसिस और गैसीकरण के सभी उत्पाद चूल्हे के बाहर वातावरण से हवा के साथ जलते हैं। किसी दिए गए कुल वायु के लिए प्राथमिक वायु की आपूर्ति बढ़ने पर दक्षता और अधिकतम लौ तापमान में सुधार होता है। लेकिन एक इष्टतम प्राथमिक वायु प्रवाह से परे, चार खपत के कारण, प्रदर्शन बिगड़ सकता है, जो संकेत देता है कि प्राथमिक वायु के रूप में स्टोइकोमेट्रिक हवा का लगभग 28-35% है। आग को स्थिर करने और नियंत्रित करने के लिए बर्नर प्लेट का उपयोग गैसीकरण उत्पादों के साथ द्वितीयक हवा के बेहतर मिश्रण के कारण आग के तापमान और थर्मल दक्षता में सुधार करता है।

TLUD चूल्हों में गैसीकरण प्रक्रिया का संख्यात्मक सिमुलेशन क्षणिक 1- आयामी गणितीय मॉडल को विकसित करके किया गया है। सिमुलेशन से प्राप्त परिणामों की तुलना प्रयोगात्मक परिणामों से भी की गई है और दोनों परिणाम आपसी सहमति वाले हैं। ईंधन कण घनत्व, ईंधन आकार और प्रकार और वायु प्रवाह दर के प्रभाव पर पैरामीट्रिक अध्ययन किया गया है। सिमुलेशन परिणाम

दिखाते हैं कि गैस संरचना ईंधन के प्रकार, आकार और कण घनत्व के प्रति अपेक्षाकृत असंवेदनशील है। यह देखा गया कि कम कण घनत्व पर, चार खपत दर बायोमास खपत दर निर्धारित करती है, जबकि उच्च घनत्व पर, इसे पायरोलिसिस दर द्वारा नियंत्रित किया जाता है। इसी प्रकार, बड़े कण आकार पर, बायोमास खपत दर उच्च तापमान प्रतिक्रिया क्षेत्र में मौजूद कणों की संख्या से सीमित होती है, जबकि छोटे कण आकार पर, खपत दर कुल कण सतह क्षेत्र द्वारा निर्धारित होती है। वायु प्रवाह दर में वृद्धि प्रयोगात्मक रूप से देखे गए विपरीत निरंतर वायु-बायोमास अनुपात को दर्शाती है। सतही वेग को स्थिर रखते हुए, जब रिएक्टर क्रॉस सेक्शन का क्षेत्र बढ़ाया जाता है, तो तापमान और गैस संरचना अपरिवर्तित रहती है और बायोमास की खपत क्षेत्र में वृद्धि के अनुपात में बढ़ जाती है - एक स्थिर SGR का संकेत मिलता है। ऐसा प्रतीत होता है कि यह मॉडल के 1-आयामी होने का परिणाम है, क्योंकि यह प्रयोगात्मक रूप से देखे गए परिणामों से भिन्न है।

प्रायोगिक और संख्यात्मक विश्लेषणों के अवलोकनों और परिणामों का उपयोग करते हुए, TLUD चूल्हों के डिजाइन के लिए एक डिजाइन दृष्टिकोण विकसित किया गया है। यह देखा गया है कि साहित्य में सुझावों के विपरीत, विशिष्ट गैसीकरण दर SGR चूल्हों की ऊंचाई और व्यास और सतही वेग दोनों पर निर्भर करती है, और रिएक्टर के क्षेत्र द्वारा ईंधन खपत दर को विभाजित करने से प्रभाव पूरी तरह से खत्म नहीं होता है। व्यास. SGR पर विभिन्न चूल्हों डिजाइन मापदंडों के प्रभाव को पूरी तरह से मापने के लिए अधिक विस्तृत और कठोर अध्ययन की आवश्यकता है। एक बार किसी दिए गए गैसीफायर के लिए SGR उपलब्ध हो जाए तदुपरांत ईंधन संयोजन, विशिष्ट गैसीकरण दर और ईंधन खपत दर की बुनियादी परिभाषाओं का उपयोग करके किसी दी गई आवश्यकता के लिए गैसीफायर के आयामों की गणना करने के लिए किया जा सकता है।

Contents

List of Figures

List of Tables

Nomenclature

Symbols and Abbreviations

A	Cross-sectional area
A/B	Air to biomass ratio
A/F	Air fuel ratio
BIS	Bureau of indian standard
C	Concentration (kmol/m^3)
CFM	Cubic feet per minute
Cge	Cold gas efficiency (%)
Cp	Specific heat (kj/kg-k)
CV	Control volume
CV_f	Calorific value
d_p	Particle diameter (mm)
D	Diameter (mm)
D_{cc}	Combustion chamber diameter
DAQ	Data acquisition system
E'''_{gen}	Energy generation per unit volume
FCR	Fuel consumption rate (kg/h)
G	Superficial velocity
g	Gravity (m/s^2)
H	Convective heat transfer coefficient
H_f	Fuel bed height
H_{cc}	Combustion chamber height
Δh_r^0	Heat of reaction (kj/k mole)
I	Intensity (w/m^2)
IAR	Inlet air ratio
K	Thermal conductivity (w/m-k) or kinetic rate constant
LHV	Lower heating value
LPG	Liquid petroleum gas

M	Mass (kg)
$\dot{m}$	Mass flow rate (kg/sec)
MW	Molecular weight
MFC	Mass flow controller
Nu	Nusselt number
P	Pressure (n/m^2)
PA	Primary air (l/min)
PM	Particulate matter
Pr	Prandtl number
$\dot{q}_{net}$	Net heat transfer
$\dot{q}_{rad}$	Net radiative heat flux (w/m^2)
R_r'''	Reaction rate ($kmol/m^3s$)
Re	Reynolds number
R_r'''	Reaction rate ($kmol/m^3s$)
Rpm	Revolution per minute
SA	Secondary air (l/min)
SGR	Specific gasification rate (kg/m^2h)
slpm	Standard liter per minute
T	Temperature (K)
TLUD	Top-lid updraft
U	Velocity
WBT	Water boiling test
Y	Volatile mass fraction
Δt_f	Flow timestep (s)
Δt_r	Reaction timestep (s)