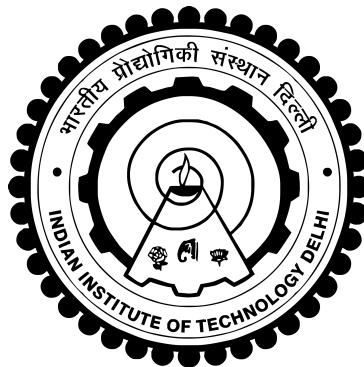


IMPROVING NATURAL DRAUGHT BIOMASS COOKSTOVES — PARAMETRIC STUDY FOR SIMPLE INTERVENTIONS

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by

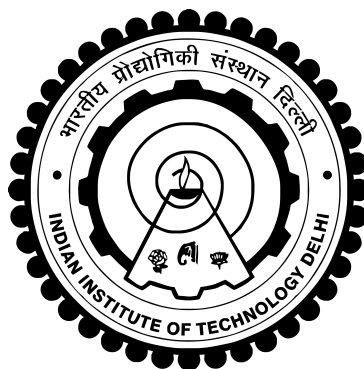
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in fulfilment of the requirements of the degree of Doctor of Philosophy

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OCTOBER 2024

CERTIFICATE

This is to certify that the thesis entitled "**Improving Natural Draught Biomass Cook-stoves — Parametric Study for Simple Interventions**" being submitted by **Mr. Thirumoorthy M** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy**, is a record of original bonafide research work carried out by him under our supervision in conformity with rules and regulations of the institute. The results presented 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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ABSTRACT

Cooking devices with combustion of fuel have been used for time immemorial the world over. While human beings learnt to burn the available fuel for suiting their cooking needs, which also evolved with time, in the past five or more decades, the cookstove researchers have focussed on improving the combustion and heat transfer in cookstoves so as to improve their thermal efficiency and emissions. The documentation of this research has also happened in primarily last five decades or so. While many designs of improved cookstoves developed by researchers have evolved over a period of time with a hope to replace the traditional ones, acceptance of improved and advanced cookstoves in the field has been limited. One important factor in this regard has been the need to change fuel and/or cooking practices with the adoption of new devices—the lesser the need for these changes, the more has been the willingness to adopt any interventions. The present work is motivated by this factor—it aims to design simple retrofits to a traditional natural draught biomass cookstove, through thorough and systematic studies on existing cookstoves. While cookstove testing has evolved so much that even there is an availability of comprehensive ISO (19867-1,3:2018 and FDIS-19869:2019) standards for testing cookstoves, scientific design process of one of the important equipment for testing, *viz.*, the emission hood, is not available in the literature. The present thesis also takes up this task to analyse emission hoods and present recommendations for its design.

The parameters affecting the airflow through a cookstove placed under two kinds of emission hoods, *viz.*, the closed emission hood and the open emission hood, have been studied through experimental measurements supported by analytical models and CFD models. Results of the analytical model show that a threshold value of negative gauge pressure at the inlet of the emission hood can be determined, beyond which the suction of the hood would affect airflow through the cookstove signifi-

cantly (change by more than 10%). For the chosen cookstove, this threshold pressure was found to be -0.15 Pa. The area of the inlet of the emission hood is determined by two factors: the area of the hood should be larger than that of the plume rising from the cookstove-vessel; for a given fan pressure rise, this area should not produce negative gauge pressures beyond threshold. In this thesis, using the turbulent plume entrainment theory, the rate of increase of plume width above the cookstove-vessel was calculated for different heights of the hood inlet above the cookstove, and a linear relation was established. Also, using CFD analysis of the hood-duct-fan region and cookstove-surrounding-hood inlet region, for the closed hood, the area of the hood inlet at which a given pressure rise at the suction fan could cause significant change of airflow through the cookstove was determined. Besides, to correct for re-circulations inside the hood making part of the area ineffective for suction, a correction is to be applied so that 85% of the actual hood area would be satisfying these two criteria. Using a combination of these results, recommendations have been made for design of an emission hood.

A traditional natural draught cookstove commonly used in the villages around Delhi was chosen for the analysis and retrofitting in the present work. Experiments on the cookstove showed that its operation was stable at input and output power values substantially higher than necessary for domestic cooking as defined by advanced biomass cookstove designs. Because of this, the efficiency was low and emissions were high. Introduction of a grate in the cookstove improved thermal efficiency, but further increased input power and had no effect on emissions. The cookstove was tested under the hood and without the hood, and no significant change in fire power was noticed between the two cases. The primary and secondary air flow rates through the stove were estimated for different fire power values by using a simple analytical model as well as a CFD model in ANSYS-Fluent.

Experimental cookstoves, which were used as laboratory analogues of the traditional cookstove with desired modifications, were tested in three phases—(i) a preliminary experiment phase to identify the feasible operating ranges of the parameters:

minimum mass of fuel bed (MMFB), primary airflow rate (PA) and ratio of total to primary airflow rates (TA/PA ratio); (ii) Experiments using central composite design over these ranges to characterise the cookstove and (iii) Out of these, conducting more experiments in the recommendable range of parameters where the cookstove operated more smoothly and efficiently. Analysing the results, the recommended range of parameters for the cookstove were identified as FBR of 20–35 g/min, PA of 10–25 slpm and SA such that total air is slightly above stoichiometric requirement for the FBR.

Based on the above, interventions were planned in the form of inserts to improve the performance of the traditional cookstove used commonly in northern part of India. The idea was to use an insert as a retrofit for the existing cookstove. Three inserts were designed and fabricated. For design of the inserts, a simplified fluid flow model through the cookstove with insert was used to get first estimates of dimensions for the desired airflow. It was observed that with the inserts, the cookstove performed more efficiently with less fire power. Particularly, with a square insert of size 12×12 cm², the fuel burning rates matched typical values used in advanced biomass cookstoves for domestic cooking—around 0.9 kg/hr (15 g/min). Thermal efficiency was increased to 25% from a value of 17% for the traditional cookstove, but the output power was about 25% lower than that in a traditional cookstove.

When the traditional cookstove was operated by an experienced operator, the emissions were quite low even without the inserts. When operated with the inserts, by the same operator, the cookstove could not perform better than the case without insert in terms of CO and PM emission factors. However, in terms of total mass of emissions of both CO and PM, the cookstove with insert had lower values than the one without it. Thus, the retrofit proposed in the present work, in the form of inserts, appears promising. With some more work, it could be an easy-to-fabricate and inexpensive intervention, capable of making the cookstove burn more efficiently and cleanly without demanding much change from the users in terms of fuel or cooking methods, and hence could be more acceptable in the field.

सार

ईंधन के दहन से चलने वाले खाना पकाने के उपकरणों का उपयोग अनादि काल से पूरी दुनिया में होता आ रहा है। मनुष्य ने अपनी खाना पकाने की जरूरतों के अनुसार उपलब्ध ईंधन को जलाना सीखा, और यह आवश्यकता समय के साथ विकसित होती गई। पिछले पाँच दशकों में, चूल्हे से संबंधित शोधकर्ताओं ने चूल्हों में दहन और ऊष्मा हस्तांतरण में सुधार पर ध्यान केंद्रित किया है, ताकि इनकी थर्मल दक्षता और उत्सर्जन में सुधार हो सके। इस शोध का दस्तावेज़ीकरण भी मुख्य रूप से पिछले पाँच दशकों में ही हुआ है।

हालांकि कई उन्नत चूल्हों के डिज़ाइन, जो शोधकर्ताओं द्वारा विकसित किए गए थे, समय के साथ विकसित हुए ताकि वे पारंपरिक चूल्हों का स्थान ले सकें, लेकिन उन्नत और सुधारित चूल्हों को क्षेत्र में सीमित स्वीकृति प्राप्त हुई है। इसका एक प्रमुख कारण यह है कि नए उपकरणों के उपयोग के साथ ईंधन और/या खाना पकाने की प्रक्रियाओं में बदलाव की आवश्यकता होती है—जितना कम बदलाव की आवश्यकता होती है, उतनी ही अधिक स्वीकृति की संभावना होती है। इस शोध का उद्देश्य इसी कारक पर आधारित है—यह मौजूदा पारंपरिक प्राकृतिक ड्राफ्ट बायोमास चूल्हे में सरल रेट्रोफिट्स डिज़ाइन करने का प्रयास करता है, ताकि उपयोगकर्ताओं को बिना किसी बड़े बदलाव के लाभ मिल सकें।

चूल्हे के परीक्षण में बहुत उन्नति हुई है, और अब चूल्हों के परीक्षण के लिए व्यापक ISO मानक भी उपलब्ध हैं। हालाँकि, परीक्षण के एक महत्वपूर्ण उपकरण, यानी उत्सर्जन हुड के वैज्ञानिक डिज़ाइन प्रक्रिया पर अभी तक साहित्य में जानकारी उपलब्ध नहीं है। इस शोध का एक उद्देश्य उत्सर्जन हुड का विश्लेषण करना और इसके डिज़ाइन के लिए सिफारिशें प्रस्तुत करना भी है।

प्रस्तुत शोध में दो प्रकार के उत्सर्जन हुड—बंद उत्सर्जन हुड और खुले उत्सर्जन हुड—के तहत चूल्हे के माध्यम से वायु प्रवाह को प्रभावित करने वाले मापदंडों का अध्ययन किया गया है, जिसमें प्रयोगात्मक मापों के साथ-साथ विश्लेषणात्मक मॉडल और CFD मॉडल का सहारा लिया गया है। विश्लेषणात्मक मॉडल के परिणामों से यह पता चला है कि उत्सर्जन हुड के इनलेट पर एक नकारात्मक गेज दबाव की एक सीमा निर्धारित की जा सकती है, जिसके बाद हुड का सक्शन चूल्हे के वायु प्रवाह को महत्वपूर्ण रूप से प्रभावित करता है। इस चूल्हे के लिए, यह सीमा दबाव -0.15 Pa पाया गया। उत्सर्जन हुड के इनलेट का क्षेत्रफल दो कारकों द्वारा निर्धारित

होता है: हुड का क्षेत्रफल चूल्हे से उठने वाले धुएं के आकार से बड़ा होना चाहिए और एक निश्चित फैन प्रेशर राइज/पंखे द्वारा उत्पन्न दाब के लिए यह क्षेत्र दबाव सीमा से अधिक न हो। इस शोध में, हुड इनलेट से विभिन्न ऊँचाइयों पर चूल्हे के ऊपर धुएं के विस्तार दर की गणना की गई और इसके आधार पर एक सीधा संबंध स्थापित किया गया। इसके अलावा, हुड-डक्ट-फैन क्षेत्र और चूल्हे-संरक्षित-हुड इनलेट क्षेत्र के CFD विश्लेषण का उपयोग करके, हुड इनलेट के उस क्षेत्र को निर्धारित किया गया जिसमें सक्शन फैन के एक निश्चित दबाव से चूल्हे के वायु प्रवाह में महत्वपूर्ण परिवर्तन हो सकता है।

दिल्ली के आसपास के गांवों में आमतौर पर उपयोग किए जाने वाले पारंपरिक प्राकृतिक ड्राफ्ट चूल्हे का चयन इस शोध कार्य के लिए किया गया था। इस चूल्हे पर किए गए परीक्षणों से पता चला कि इसके संचालन के इनपुट और आउटपुट पावर मूल्य काफी अधिक थे, जो घरेलू खाना पकाने के लिए डिज़ाइन किए गए उन्नत बायोमास चूल्हों की आवश्यकताओं से अधिक थे। इसी वजह से, इसकी दक्षता कम थी और उत्सर्जन अधिक था। चूल्हे में एक ग्रेट (जाली) जोड़ने से थर्मल दक्षता में सुधार हुआ, लेकिन इससे इनपुट पावर में और वृद्धि हुई और उत्सर्जन पर इसका कोई प्रभाव नहीं पड़ा। चूल्हे को हुड के साथ और बिना हुड के परीक्षण किया गया और दोनों ही स्थितियों में फायर पावर में कोई महत्वपूर्ण बदलाव नहीं देखा गया। विभिन्न फायर पावर मूल्यों के लिए चूल्हे के प्राथमिक और द्वितीयक वायु प्रवाह दरों का अनुमान सरल विश्लेषणात्मक मॉडल और ANSYS-Fluent में CFD मॉडल का उपयोग करके लगाया गया।

पारंपरिक चूल्हे के प्रदर्शन को बेहतर बनाने के लिए इसमें कुछ इनसर्ट्स के रूप में सुधार किए गए। इन इनसर्ट्स को चूल्हे के एयरफ्लो को नियंत्रित करने के लिए डिज़ाइन किया गया था ताकि यह अधिक कुशलता से और कम फायर पावर के साथ संचालित हो सके। विशेष रूप से, 12×12 वर्ग सेंटीमीटर आकार के इनसर्ट के साथ, चूल्हे का ईंधन दहन दर उन्नत बायोमास चूल्हों में घरेलू खाना पकाने के लिए उपयोग की जाने वाली सामान्य दरों के अनुरूप पाई गई, जो कि लगभग 0.9 किग्रा/घंटा (15 ग्राम/मिनट) थी। थर्मल दक्षता 17% से बढ़कर 25% हो गई, लेकिन आउटपुट पावर पारंपरिक चूल्हे की तुलना में लगभग 25% कम हो गई।

जब एक अनुभवी उपयोगकर्ता द्वारा चूल्हे को बिना इनसर्ट्स के चलाया गया, तो CO और PM उत्सर्जन कारकों के मामले में उत्सर्जन दर पहले से काफी कम थी। इनसर्ट्स के साथ, एक ही

ऑपरेटर द्वारा चूल्हे का प्रदर्शन CO और PM के उत्सर्जन कारकों के संदर्भ में पहले से बेहतर नहीं पाया गया। हालांकि, इनसर्ट के साथ कुल उत्सर्जन मात्रा, CO और PM के संदर्भ में, इनसर्ट के बिना चूल्हे की तुलना में कम थी।

इस प्रकार, इस शोध में प्रस्तावित सुधार, एक सस्ते, सरल और प्रभावी रेट्रोफिट के रूप में संभावनापूर्ण प्रतीत होता है। यह चूल्हे को अधिक कुशलता और सफाई से जलाने में सक्षम बना सकता है और उपयोगकर्ताओं से ईंधन या खाना पकाने की विधियों में कोई विशेष बदलाव की मांग नहीं करता है, जिससे इसे क्षेत्र में अधिक स्वीकार्यता प्राप्त हो सकती है।

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Nomenclature

Acronyms

A / F	Air to fuel ratio
ABC	Advanced Biomass Cookstoves
ANOVA	Analysis of variance
BIS	Bureau of Indian Standards
CAD	Computer-Aided Design
CC	Combustion chamber
CCD	Central composite design
CEH	Closed emission hood
CFD	Computational Fluid Dynamics
CO	Carbon-monoxide
DAQ	Data Acquisition System
DOE	Design of experiments
EH	Emission Hood
FBR	Fuel burning rate
IC	Improved Cookstoves
lpm	Liter per minute
MMFB	Minimum mass of fuel bed
OEH	Open emission hood
PA	Primary Air
PM	Particulate matter
ppm	parts per million
rpm	Revolution per minute
RSM	Response surface methodology
SA	Secondary Air
slpm	Standard litre per minute
TA	Total air
WBT	Water Boiling Test

Greek Letters

β	Coefficient of thermal expansion
μ	Viscosity
ϕ	Void fraction of the bed
ρ	Density
σ	Stefan Boltzmann constant
τ	Stress
ε_b	Emissivity of fuel bed
ε_w	Emissivity of cookstove wall

Symbols

ΔP_{bed}	Pressure drop due to fuel bed
ΔP_{char}	Pressure drop due to char bed
$\dot{m}$	Mass of flow rates of air
A_{bf}	Surface area of the front side of the fuel bed
A_{bt}	Surface area of the top of fuel bed
A_w	Surface area of top fuel bed
B	Plume width
C_p	Specific heat of air
d_v	Vessel diameter
F	View factor
g	Acceleration due to gravity
G_{vh}	Distance between the vessel and hood
h	Enthalpy of fluid
k_{bend}	Pressure loss due to 90° bend of flow
k_{enter}	Entrance loss coefficient
k_{exit}	Exit loss coefficient
k_{exp}	Pressure loss due to fluid expansion
k_f	Thermal conductivity of the fluid
k_w	Thermal conductivity of wall
P	Static pressure of air
P_H	Pressure at the inlet plane of the hood
Pr	Prandtl number
Q_{bed}	Rate of heat release in fuel bed
Q_{gas}	Rate of heat in gas region
Q_{loss}	Rate of heat losses
S_h	Heat source
T_∞	Ambient temperature
t_w	Thickness of wall
v	Velocity of air
W_P	Initial plume width
Z	Elevation