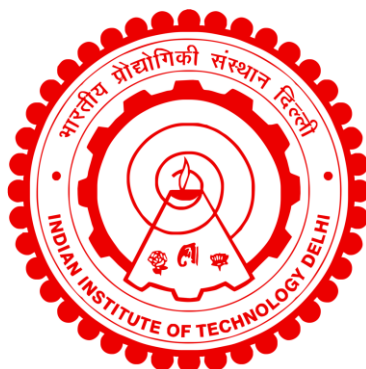


PERFORMANCE ENHANCEMENT AND EMISSIONS REDUCTION IN JAGGERY PLANTS THROUGH CLEAN COMBUSTION USING PROCESSED AGRO-RESIDUE WASTES

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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Performance Enhancement and Emissions Reduction in Jaggery Plants Through Clean Combustion using Processed Agro-residue Wastes

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

August 2025

DEDICATED
TO
MY BELOVED PARENTS

DECLARATION

I hereby declare that the work presented here in the thesis entitled “Performance Enhancement and Emissions Reduction in Jaggery Plants Through Clean Combustion Using Processed Agro-residue Wastes” 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, has 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 “**Performance Enhancement and Emissions Reduction in Jaggery Plants Through Clean Combustion Using Processed Agro-residue Wastes**” being submitted by **Mr. Alok Kumar** 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 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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(Alok Kumar)

ABSTRACT

Jaggery, commonly known as 'Gur' in the Indian subcontinent, is a traditional sweetener produced by concentrating the juice extracted from sugarcane or palm trees into a solid or semi-solid form. The fibrous residue obtained from sugarcane crushing, known as bagasse, is sun-dried and subsequently used as a primary fuel source in the jaggery production process. The traditional jaggery production, while culturally significant and accessible, suffers from low thermal efficiency, high emissions, and excessive bagasse consumption. These limitations highlight the need for technological interventions aimed at improving energy efficiency, reducing environmental impact, and optimizing resource utilization in the jaggery production process. This thesis delves into a comprehensive experimental and numerical investigation into the thermal performance and gaseous emissions of traditional and modified four-pan jaggery production units. The present study aims to assess the energy and exergy efficiencies based on resource consumption and transformations occurring in the sugarcane-based jaggery manufacturing process. Initially, an exergy analysis of the traditional jaggery unit is conducted using experimental data, thermodynamic relations, and specific exergy values for the different system components. This analysis is performed for both summer and winter seasons. The results revealed that the exergy sustainability scores are low during both seasons, indicating significant environmental impacts and inefficiencies in the process. The experimental energy and exergy efficiencies are found to be higher in the summer season compared to winter. Specifically, the energy efficiency is recorded at 25.72% in summer and 17.62% in winter, while the exergy efficiency of bagasse combustion is 3.69% in summer and 2.89% in winter. These differences are attributed to higher ambient temperatures, lower moisture content in bagasse, and greater brix content in sugarcane during the summer. The exergy destruction due to combustion is significant, calculated as 85.28% in winter and 85.77%

in summer. This is primarily due to thermal irreversibilities in combustion and heat transfer processes. The operation of the four-pan jaggery unit is found to be more eco-friendly during the summer due to a higher Exergy-Based Index (EBI). However, the sustainability index remained low for both seasons, suggesting that although renewable energy sources are used, the environmental emissions are considerable. To improve exergy efficiency, sustainability index, and EBI, it is necessary to reduce the destruction number (DN), environmental destruction coefficient (EDC), and exergy destruction index (EDI). The emissions data for the traditional jaggery unit showed that carbon monoxide (CO) levels ranged from 23,500 to 65,000 ppm, nitrogen oxides (NO_x) from 70 to 855 ppm, and sulphur dioxide (SO₂) from 1,720 to 3,350 ppm.

A computational fluid dynamics (CFD) model is developed and validated against experimental results for traditional unit, demonstrating good agreement in terms of thermal efficiency and flue gas temperature profiles. Several design variations are analysed numerically, including changes to the inlet position and area, the application of thermal insulation, the implementation of a deep-pan strategy, and zig-zag furnace flow design. The study found that radiative heat transfer is the dominant mode of heat transfer to the pans. Alterations to the inlet area and location had minimal impact on heat transfer to the pans due to the minor role of convection in this process. This finding differs from previous literature, likely due to the higher flue gas temperatures in the present setup. The flow dynamics are not significantly affected by these geometrical changes. The deep-pan strategy showed significant potential for enhancing thermal efficiency, which increased to 26%, marking a 30–40% improvement over the baseline unit. This improvement is mainly due to a larger radiative heat exchange surface. Additionally, Pan 4, which is the first to receive the flue gases, experienced increased heat transfer rate due to flow impingement and enhanced turbulence caused by cavity formations between the pans. Thermal insulation using ceramic blankets is also studied, with

thicknesses ranging from 1 to 4 inches. The analysis found that a 2-inch thickness is optimal, providing effective thermal retention with no significant gains beyond this point. Insulation at the top furnace wall near the pan sides is found to be most effective. When combined with the deep-pan strategy, thermal insulation further improved performance. Specifically, the thermal efficiency increased to 25.7% with 2-inch insulation and to 26.1% with 4-inch insulation, compared to the baseline of 18.82%. However, due to cost considerations, 2-inch insulation is deemed optimal. A zig-zag flow furnace design is also tested, with multiple slot hole geometries. These changes showed minimal impact on performance in the absence of insulation. However, when combined with insulation and the deep-pan strategy, the zig-zag configuration achieved a thermal efficiency of 25.12% without insulation and 26.60% with insulation. In this design strategy, convective heat transfer became the dominant mode, which is a contrast to the baseline case where radiative heat transfer dominated.

An experimental evaluation of a burner-integrated modified jaggery unit, insulated with a 2-inch ceramic blanket, showed substantial improvement in thermal performance. The thermal efficiency ranged from 42% to 45%, while emissions are significantly reduced. The CO emissions dropped to 120–300 ppm, NO_x to 171–785 ppm, and SO₂ to 1.50–121 ppm. Numerical simulations for this modified unit showed strong agreement with experimental data in terms of both thermal efficiency and slot hole temperature profiles. Like the zig-zag furnace, the modified unit exhibited a dominance of convective heat transfer. Further numerical studies on the modified jaggery unit incorporating deep-pan and mixed-pan strategies revealed remarkable thermal performance improvements. The deep-pan strategy increased thermal efficiency to 53.1%, while the mixed-pan strategy achieved a peak efficiency of 63.27%, underscoring the effectiveness of combining structural optimization with thermal management.

गुड़, जिसे भारतीय उपमहाद्वीप में सामान्यतः 'गुड़' कहा जाता है, एक पारंपरिक मिठाई है जिसे गन्ने या ताड़ के पेड़ों से निकाले गए रस को गाढ़ा करके ठोस या अर्ध-ठोस रूप में तैयार किया जाता है। गन्ने की पेराई से प्राप्त रेशेदार अवशेष, जिसे बगास कहा जाता है, को धूप में सुखाकर गुड़ उत्पादन प्रक्रिया में प्रमुख ईंधन के रूप में उपयोग किया जाता है। हालाँकि पारंपरिक गुड़ उत्पादन सांस्कृतिक रूप से महत्वपूर्ण और सुलभ है, लेकिन इसमें तापीय दक्षता कम होती है, उत्सर्जन अधिक होता है और बगास की अत्यधिक खपत होती है। इन सीमाओं को देखते हुए, ऊर्जा दक्षता बढ़ाने, पर्यावरणीय प्रभावों को कम करने और संसाधनों के इष्टतम उपयोग के लिए तकनीकी हस्तक्षेप की आवश्यकता है। यह शोध कार्य पारंपरिक और परिवर्तित चार-कढ़ाही वाले गुड़ इकाइयों की तापीय प्रदर्शन और गैसीय उत्सर्जनों का एक व्यापक प्रयोगात्मक एवं संख्यात्मक (numerical) अध्ययन प्रस्तुत करता है। अध्ययन का उद्देश्य गन्ने पर आधारित गुड़ निर्माण प्रक्रिया में ऊर्जा और एक्सर्जी दक्षताओं का संसाधन खपत और होने वाले रूपांतरणों के आधार पर मूल्यांकन करना है। प्रारंभ में पारंपरिक गुड़ इकाई की एक्सर्जी विश्लेषण किया गया, जिसमें प्रयोगात्मक आंकड़ों, उष्मागतिकी (Thermodynamic) समीकरणों और विभिन्न प्रणाली घटकों के लिए विशिष्ट एक्सर्जी मानों का उपयोग किया गया। यह विश्लेषण ग्रीष्मकाल और शीतकाल दोनों ऋतुओं के लिए किया गया। परिणामों से पता चला कि दोनों मौसमों में एक्सर्जी स्थायित्व स्कोर (Exergy Sustainability Score) कम था, जिससे पता चलता है कि प्रक्रिया में पर्यावरणीय प्रभाव और अक्षमताएँ काफी अधिक हैं। प्रयोगात्मक रूप से ऊर्जा और एक्सर्जी दक्षताएँ गर्मियों में सर्दियों की तुलना में अधिक पाई गईं। गर्मियों में ऊर्जा दक्षता 25.72% और सर्दियों में 17.62% दर्ज की गई, जबकि बगास दहन की एक्सर्जी दक्षता गर्मियों में 3.69% और सर्दियों में 2.89% रही। यह अंतर उच्च परिवेश तापमान, बगास में कम नमी और गन्ने में अधिक ब्रिक्स कंटेंट के कारण था। दहन के कारण एक्सर्जी नष्ट होना काफी अधिक था — सर्दियों में 85.28% और गर्मियों में

85.77% — जो मुख्यतः दहन और ऊष्मा स्थानांतरण प्रक्रियाओं में तापीय अपारिवर्तनीयताओं के कारण था। चार-कढ़ाही प्रणाली का संचालन ग्रीष्मकाल में अधिक पर्यावरण-अनुकूल पाया गया, क्योंकि इसमें उच्च एक्सर्जी आधारित सूचकांक (EBI) दर्ज हुआ। हालाँकि, स्थायित्व सूचकांक (Sustainability Index) दोनों मौसमों में कम रहा, यह दर्शाता है कि नवीकरणीय ऊर्जा स्रोतों के उपयोग के बावजूद पर्यावरणीय उत्सर्जन पर्याप्त है। एक्सर्जी दक्षता, स्थायित्व सूचकांक और EBI में सुधार के लिए Destruction Number (DN), Environmental Destruction Coefficient (EDC) और Exergy Destruction Index (EDI) को कम करना आवश्यक है। पारंपरिक गुड़ इकाई के लिए उत्सर्जन डेटा के अनुसार कार्बन मोनोऑक्साइड (CO) 23,500 से 65,000 ppm, नाइट्रोजन ऑक्साइड (NO_x) 70 से 855 ppm, और सल्फर डाइऑक्साइड (SO₂) 1,720 से 3,350 ppm तक दर्ज किया गया।

एक पारंपरिक इकाई के लिए विकसित किया गया कम्प्यूटेशनल फ्लूइड डायनेमिक्स (CFD) मॉडल प्रयोगात्मक परिणामों से अच्छी तरह मेल खाता है, विशेषकर तापीय दक्षता और फ्ल्यू गैस तापमान प्रोफाइल के संदर्भ में। कई डिज़ाइन बदलावों का संख्यात्मक विश्लेषण किया गया — जैसे कि इनलेट की स्थिति और क्षेत्र में बदलाव, थर्मल इंसुलेशन का उपयोग, डीप-पैन रणनीति और ज़िग-ज़ैग भट्टी प्रवाह डिज़ाइन। अध्ययन से यह पाया गया कि पैनों को ऊष्मा स्थानांतरण में विकिरणीय ऊष्मा (Radiative Heat Transfer) प्रमुख भूमिका निभाती है। इनलेट क्षेत्र और स्थिति में बदलाव से ऊष्मा स्थानांतरण पर विशेष प्रभाव नहीं पड़ा क्योंकि संवहन (Convection) का योगदान न्यूनतम पाया गया। यह निष्कर्ष पिछले साहित्य से अलग है, संभवतः वर्तमान प्रणाली में उच्च फ्ल्यू गैस तापमान के कारण। डीप-पैन रणनीति ने तापीय दक्षता में उल्लेखनीय सुधार दिखाया, जो बढ़कर 26% हो गई — जो कि बेसलाइन इकाई की तुलना में 30–40% अधिक है। इसका मुख्य कारण बढ़ी हुई विकिरणीय ऊष्मा विनिमय सतह है। इसके अतिरिक्त, पैन 4 — जो सबसे पहले फ्ल्यू गैस प्राप्त करता है — में कैविटी निर्माण और प्रवाह टकराव के कारण ऊष्मा स्थानांतरण दर अधिक रही। सिरैमिक ब्लैकेट से थर्मल इंसुलेशन (1 से 4 इंच मोटाई) का भी विश्लेषण किया गया। 2 इंच की मोटाई को सबसे उपयुक्त

पाया गया क्योंकि इससे पर्याप्त ऊष्मा संरक्षण मिला और उससे अधिक मोटाई से कोई महत्वपूर्ण लाभ नहीं मिला। पैन के पास ऊपरी भट्टी दीवार पर इंसुलेशन सबसे प्रभावी रहा। जब इसे डीप-पैन रणनीति के साथ जोड़ा गया, तो तापीय दक्षता में और सुधार हुआ: 2-इंच इंसुलेशन के साथ दक्षता 25.7% और 4-इंच के साथ 26.1% हो गई, जबकि बेसलाइन मात्र 18.82% थी। हालांकि लागत को देखते हुए 2-इंच इंसुलेशन को उपयुक्त माना गया। ज़िग-ज़ैग फ्लो डिज़ाइन का भी परीक्षण किया गया, जिसमें कई स्लॉट होल ज्योमेट्री शामिल थीं। केवल ज़िग-ज़ैग बदलाव से खास लाभ नहीं मिला, लेकिन जब इसे इंसुलेशन और डीप-पैन रणनीति के साथ जोड़ा गया, तो बिना इंसुलेशन के दक्षता 25.12% और इंसुलेशन के साथ 26.60% तक पहुँच गई। इस डिज़ाइन में संवहन ऊष्मा स्थानांतरण प्रमुख बन गया, जो कि बेसलाइन स्थिति के विपरीत है जहाँ विकिरणीय स्थानांतरण प्रमुख था।

एक बर्नर-युक्त संशोधित गुड़ इकाई (2-इंच सिरैमिक इंसुलेशन सहित) के प्रयोगात्मक मूल्यांकन में तापीय प्रदर्शन में उल्लेखनीय सुधार देखा गया। इसकी तापीय दक्षता 42% से 45% रही और उत्सर्जन में भी भारी कमी आई। CO उत्सर्जन 120–300 ppm, NO_x 171–785 ppm और SO₂ 1.50–121 ppm तक गिर गया। संशोधित इकाई के लिए किए गए संख्यात्मक अनुकरण (Simulation) प्रयोगात्मक आंकड़ों से अच्छी तरह मेल खाते हैं। ज़िग-ज़ैग भट्टी की तरह ही, इस इकाई में भी संवहन ऊष्मा स्थानांतरण प्रमुख पाया गया। संशोधित इकाई में डीप-पैन और मिक्स-पैन रणनीतियों को शामिल कर किए गए अतिरिक्त संख्यात्मक अध्ययनों ने और भी बेहतर तापीय प्रदर्शन दिखाया। डीप-पैन रणनीति से तापीय दक्षता 53.1% तक पहुँची, जबकि मिक्स-पैन रणनीति ने 63.27% तक की दक्षता हासिल की, जो यह दर्शाता है कि संरचनात्मक अनुकूलन और थर्मल प्रबंधन का संयुक्त प्रभाव अत्यधिक प्रभावी है।

CONTENTS

Declaration		i
Certificate		ii
Acknowledgements		iii
Abstract		iv
Contents		x
List of Figures		xiv
List of Tables		xix
Nomenclature		xxi
Chapter 1	Introduction	1
	1.1 Background	1
	1.2 Jaggery composition	4
	1.3 Nutritional content	5
	1.4 Types of jaggery	6
	1.4.1 Liquid jaggery	6
	1.4.2 Granular jaggery	7
	1.4.3 Solid jaggery	8
	1.5 Motivation for present study	8
	1.6 Objectives of the present research	9
	1.6 Organization of the thesis	10
Chapter 2	Literature Review	14
	2.1 Introduction	14
	2.2 Jaggery production	14
	2.3 Processes involved in jaggery production	16
	2.4 Technological advancement in jaggery units	20
	2.4.1 Sugarcane processing and dry bagasse	20
	2.5 Modifications in jaggery furnace	22
	2.6 Modifications in pans	24
	2.7 Utilization of solar energy	29
	2.8 Energy and exergy analysis	31
	2.9 Numerical study	32

	2.10 Emission reduction potential	38
	2.11 Biomass pellet	40
	2.12 Biomass Gasification	41
	2.12.1 Gasification phenomena	42
	2.12.2 Gasification reactors	43
	2.13 Research gaps	46
Chapter 3	Experimental testing facility and methodology	48
	3.1 Introduction	48
	3.2 Testing facility and methodology	48
	3.2.1 Energy efficiency	52
	3.2.2 Exergy efficiency	55
	3.2.3 Sustainability indicators	60
	3.2.4 Gaseous emissions	61
	3.3 Biomass characterization	63
	3.3.1 Proximate analysis	64
	3.3.2 Ultimate analysis	66
	3.3.3 Calorific value	67
	3.4 Measuring Instruments	68
	3.4.1 Refractometer	68
	3.4.2 Temperature scanner	69
	3.4.3 Gas Analyzer	69
	3.4.4 Microbalance	70
	3.4.5 Liquid Level Indicator	70
	3.4.6 Weighing balance	70
Chapter 4	Thermal performance of a traditional jaggery unit	72
	4.1 Introduction	72
	4.2 Experimental investigations of traditional four-pan jaggery plant	72
	4.3 Bagasse characterization	76
	4.4 Air-Fuel and Equivalence Ratio	77
	4.5 Mass balance	79
	4.6 Thermal performance analysis	81
	4.7 Energy analysis	82

	4.8 Exergy analysis	83
	4.9 Implications and scope of process improvement	87
	4.10 Energy saving	88
	4.11 Uncertainty in experiment	89
	4.12 Sustainability indicators	91
	4.13 Comparative analysis of exergy and sustainability with literature	92
	4.14 Density and velocity of flue gas	93
	4.15 Chimney draught	94
	4.16 Gaseous emissions	95
	4.17 Economic analysis	96
	4.18 Summary	98
Chapter 5	Numerical analysis of a traditional jaggery unit	100
	5.1 Introduction	100
	5.2 Field data measurement and analysis	101
	5.3 Mass and energy balance for sugarcane juice and heat transfer coefficient estimation	104
	5.4 Flue gas flow rate estimation	106
	5.5 Computational fluid dynamics modelling	108
	5.5.1 Computational domain	112
	5.5.2 Grid independency test	114
	5.5.3 Solver setup and boundary conditions	115
	5.6 Numerical tool validation and results in the baseline case	117
	5.6.1 CFD Validation with experimental results	123
	5.7 Design improvement strategies	126
	5.7.1 Effect of inlet position and inlet area on thermal efficiency	126
	5.7.2 Deep-pan strategy	127
	5.8 Zig-zag furnace	133
	5.8.1 Zig-zag pathway design	133
	5.8.2 Zig-zag pathway having variable dimensions	135
	5.8.3 Deep-pan strategy with zig-zag furnace	140
	5.9 Effect of thermal insulation	145

	5.9.1 Comparative effect of thermal insulation baseline, zig-zag furnace and deep-pan zig-zag furnace	149
	5.10 Summary	150
Chapter 6	Pellet-based burner integrated with modified jaggery unit	152
	6.1 Introduction	152
	6.2 Proximate and ultimate analysis of biomass pellets	153
	6.3 Traditional jaggery unit	154
	6.4 Modified jaggery unit	154
	6.4.1 Pellet-based burner	155
	6.4.2 Modified jaggery furnace	156
	6.5 Experimental uncertainty	162
	6.6 Computational fluid dynamics modelling of modified unit	163
	6.6.1 Computational domain	164
	6.6.2 Solver setup and boundary conditions	166
	6.7 Numerical tool validation and results in the modified jaggery unit	168
	6.7.1 CFD Validation with experimental results	175
	6.8 Deep-pan strategy in modified jaggery unit	177
	6.9 Mixed-pan strategy	184
	6.10 Summary	189
Chapter 7	Overall Conclusions and Recommendations	191
	7.1 Overall conclusions	191
	7.2 Limitations and weakness of present research	195
	7.2 Recommendations for future work	196
	References	199
	Appendices	209
	List of Publications	212
	Achievements	214
	About the Author	215

LIST OF FIGURES

Figure 1.1	Jaggery production from the financial year 2012 to 2023	2
Figure 2.1	Processes involved in sugarcane based jagger production	15
Figure 2.2	Sugarcane producing countries in 2023	16
Figure 2.3	Types of jaggery units (a) Single-pan (b) Two-pan (c) Three-pan (d) Four-pan	19
Figure 2.4	Modified main pan and gutter pan	25
Figure 2.5	The schematic of two-pan jaggery unit	27
Figure 2.6	The two-pan semi-automatic jaggery unit	28
Figure 2.7	Jaggery unit having provision for primary and secondary air	33
Figure 2.8	Contours for jaggery unit (a) Velocity (b) Carbon-dioxide concentration (c) Moisture concentration (d) Temperature	34
Figure 2.9	Computational domain for CFD simulation	35
Figure 2.10	Computational domains: (a) Domain 1, (b) Domain 2 and (c) Domain 3.	36
Figure 2.11	Three-dimensional geometry for numerical study (a) Four-pan jaggery unit (b) finned fire-tube pan: Isometric view (c) finned fire-tube pan: Front view	37
Figure 2.12	Comparative emissions from jaggery units (a) CO (b) PM (c) CO ₂	40
Figure 2.13	Several type of reactors: (a) Updraft (b) Downdraft (c) Bubbling fluidized-bed (Basu et al., 2010)	45
Figure 3.1	Schematic diagram of four-pan jaggery unit (a) Traditional unit (b) Modified unit with integrated biomass burner	51
Figure 3.2	Photographic view of jaggery unit (a) Traditional unit (b) Modified unit	52
Figure 3.3	Control volume analysis for jaggery furnace	56
Figure 3.4	Pictorial view instruments used during experimental investigation (a) Muffle furnace (b) Hot air oven (c) CHNS/O analyzer (d) Bomb calorimeter (e) Refractometer (f) Temperature scanner (g) Gas analyzer (h) Microbalance (i) Liquid level indicator (j) Weighing balance	64

Figure 3.5	Pictorial view of CHNS analyzer	67
Figure 3.6	Bomb calorimeter	68
Figure 4. 1	The traditional four-pan jaggery plant (a) Schematic and (b) photographic	75
Figure 4. 2	The seasonal variation of (a) Air-fuel ratio and (b) equivalence ratio with flame temperature	78
Figure 4. 3	Mass balance (a) Winter season and (b) Summer season	80
Figure 4. 4	Energy balance (a) Winter season and (b) Summer season	83
Figure 4. 5	Energy and exergy performance in winter and summer	86
Figure 4. 6	Combustion performance in winter and summer	86
Figure 4. 7	Process Y integrated with jaggery process in (a) Winter season and (b) Summer season	88
Figure 5. 1	Pictorial view of four-pan jaggery units and instrument used during experimental investigation (a) Furnace Inlet (b) Working on Pans (c) Chimney outlet (d) Refractometer (d) Temperature scanner (e) Gas analyser (f) Stake sampler with S-type pitot tube	102
Figure 5. 2	Solution algorithm	103
Figure 5. 3	Four-pan jaggery unit indicating geometry (all the dimensions are in cm), domains and boundaries	113
Figure 5. 4	The traditional four-pan jaggery unit (a) Mesh visualization (b) Temperature profile at furnace outlet with varying total mesh count	115
Figure 5. 5	Temperature contours (a) With radiation model enabled (b) Without radiation modelling	118
Figure 5. 6	Heat flux contour (a) With radiation model enabled (b) Without radiation modelling	118
Figure 5. 7	The variation of average heat flux for each pan obtained through simulation with ($T_p - T_j$) which is simulated pan temperature and experimental juice temperature	120
Figure 5. 8	Velocity contours (a) With radiation model enabled and (b) Without radiation modelling	121
Figure 5. 9	Heat utilized in different pans as predicted in simulations with and without the radiation model.	122
Figure 5. 10	Heat loss from furnace walls	123

Figure 5. 11	Furnace outlet temperature in duct (a) CFD validation with experimental (b) Probe locations	125
Figure 5. 12	Flue-gas flow domain in four-pan jaggery unit (a)Bottom inlet (b) Front inlet upward (c) Front inlet downward	126
Figure 5. 13	Pictorial view of the pans (a) Deep-pans (b)Traditional pans (All the dimensions are in cm)	128
Figure 5. 14	Comparative temperature contours (a)Deep-pan strategy (b) Baseline case	129
Figure 5. 15	Heat utilized in different pans	129
Figure 5. 16	The heat flux contour for (a) Deep pan strategy (b) Baseline case obtained through simulations	130
Figure 5. 17	The average heat flux for each pan for the deep pan strategy obtained through simulation with $(T_p - T_j)$ difference pan temperature and juice temperature	131
Figure 5. 18	Heat transfer coefficient at bottom of pans obtained through simulation for baseline and deep-pan strategy case	132
Figure 5. 19	The schematic of zig-zag flow based jaggery unit	133
Figure 5. 20	The schematic of different zig-zag flow based jaggery unit designs	134
Figure 5. 21	Temperature profile of jaggery unit (a)Baseline case (b) Zig-zag furnace	136
Figure 5. 22	Heat utilized in different pans in Zig-zag furnace	136
Figure 5. 23	The heat flux contour for (a) Baseline case (b) zig-zag furnace case obtained through simulations	137
Figure 5. 24	Velocity contours of jaggery unit (a) Basline case (b) Zig-zag jaggery furnace	138
Figure 5. 25	Heat loss from furnace walls	139
Figure 5. 26	The average heat flux for each pan for the zig-zag furnace obtained through simulation with $(T_p - T_j)$ difference pan temperature and juice temperature	140
Figure 5. 27	Comparative temperature contours (a) Deep-pan strategy (b) Baseline case	141
Figure 5. 28	Heat utilized in different pans	142

Figure 5. 29	The heat flux contour for (a) Baseline case (b) Deep pan strategy with zig-zag furnace obtained through simulations	143
Figure 5. 30	The average heat flux for each pan for the deep pan strategy obtained through simulation with $(T_p - T_j)$ difference pan temperature and juice temperature	144
Figure 5. 31	(a) The inner thermal insulation of a traditional four-pan jaggery furnace. (b) Thermal efficiency and exhaust heat loss from furnace	145
Figure 5. 32	Thermal efficiency and exhaust heat loss from the furnace in an insulated deep-pan strategy furnace	147
Figure 5. 33	The average heat flux for each pan for the insulated zig-zag furnace obtained through simulation with $(T_p - T_j)$ difference pan temperature and juice temperature	148
Figure 5. 34	The average heat flux for each pan for the insulated deep-pan strategy-based zig-zag furnace is obtained through simulation with $(T_p - T_j)$ difference pan temperature and juice temperature	149
Figure 6. 1	Heat utilized in different pans	154
Figure 6. 2	Biomass based horizontally fired pellet burner (a) Three-dimensional schematic diagram (b) Geometric dimensions	156
Figure 6. 3	Schematic diagram of modified unit (a) four-pan Jaggery unit (b) Four-pan Jaggery unit integrated with burner	157
Figure 6. 4	The variation of parameters with respect to flame temperature in modified jaggery unit (a) AFR (b) Equivalence ratio	158
Figure 6. 5	The sanky diagram of energy balance	161
Figure 6. 6	The heat utilised in pans	161
Figure 6. 7	Modified zigzag jaggery unit	164
Figure 6. 8	Mesh visualization of modified unit	166
Figure 6. 9	Temperature contours (a) With radiation model enabled (b) Without radiation modelling	170
Figure 6. 10	Heat flux contour (a) With radiation model enabled (b) Without radiation modelling	171
Figure 6. 11	The variation of average heat flux for each pan obtained through simulation with $(T_p - T_w)$ which is simulated pan temperature and experimental water temperature	172

Figure 6. 12	Velocity contours (a) With radiation model enabled and (b) Without radiation modelling	173
Figure 6. 13	Heat utilized in different pans as predicted in simulations with and without the radiation model.	175
Figure 6. 14	Furnace outlet temperature in duct (a) CFD validation with experimental (b) Probe locations	177
Figure 6. 15	Modified zig-zag unit with deep-pan strategy	178
Figure 6. 16	Comparative temperature contours (a) Modified Baseline case (b) Deep-pan strategy	179
Figure 6. 17	Heat utilized in different pans as predicted in simulations with and without the radiation model	180
Figure 6. 18	The heat flux contour for (a)Modified baseline case (b) Deep pan strategy obtained through simulations	181
Figure 6. 19	The average heat flux for each pan for the deep pan strategy obtained through simulation with $(T_p - T_w)$ difference pan temperature and water temperature	182
Figure 6. 20	Mixed-pan strategy in modified unit	184
Figure 6. 21	Comparative temperature contours of modified jaggery unit (a) Deep-pan strategy (b)Mixed-pan strategy	185
Figure 6. 22	Heat utilized in different pans as predicted in simulations with and without the radiation model	186
Figure 6. 23	The heat flux contour for (a) Deep pan strategy (b) Mixed-pan strategy obtained through simulations	187
Figure 6. 24	The average heat flux for each pan for the mixed-pan strategy obtained through simulation with $(T_p - T_w)$ difference pan temperature and water temperature	188

LIST OF TABLES

Table 1.1	Minerals content in jaggery	5
Table 2.1	Changes or improvements in different jaggery units	32
Table 3.1	Thermophysical properties of sugarcane juice	53
Table 4.1	Temperature variation for winter and summer	74
Table 4.2	List of instruments	76
Table 4.3	Proximate analysis and ultimate analysis of bagasse	76
Table 4.4	Exergy balance of jaggery production process in winter and summer	85
Table 4.5	Exergy balance for the bagasse combustion in winter and summer	86
Table 4.6	Mean and uncertainty for several parameters	90
Table 4.7	Comparative sustainability indicators	91
Table 4.8	Comparative analysis of sustainability indicators with literature	93
Table 4.9	Density and velocity of flue in traditional unit	94
Table 4.10	Chimney draught in winter and summer	95
Table 4.11	Gaseous pollutants of traditional jaggery plant	96
Table 4.12	Capital cost of four-pan jaggery plant	97
Table 4.13	Total annual operating and maintenance cost	97
Table 4.14	Total Cost analysis of four-pan jaggery plant	97
Table 5.1	Heat transfer coefficient (HTC) for different pans.	105
Table 5.2	The flue gas flow rate at average flame temperature	108
Table 5.3	Mesh details for four-pan jaggery unit.	114
Table 5.4	Material and its properties used in CFD simulations.	116
Table 5.5	Boundary conditions involved in simulation.	116
Table 5.6	Thermal efficiency for different inlet areas and orientation	127
Table 5.7	Thermal efficiency for different insulated jaggery units	150
Table 6.1	Proximate analysis and ultimate analysis of pellet	153
Table 6.2	Temperature in slot holes, furnace inlet and chimney	160
Table 6.3	Optimized Feed and air flow rate in furnace	160
Table 6.4	Gaseous pollutants of modified jaggery unit	163
Table 6.5	Comparative gaseous pollutants of traditional and modified jaggery unit	163
Table 6.6	Mesh details for four-pan jaggery unit.	166

Table 6.7	Material and its properties used in CFD simulations.	167
Table 6.8	Boundary conditions involved in simulation.	168
Table 6.9	The area weighted average of heat flux in different pans	171

NOMENCLATURE

$E_{bagasse}$	Bagasse heat input (MJ)
T_b	Boiling temperature of water (K)
Ex_0	Chemical exergy (MJ)
$E_{Jaggery}$	Energy content in jaggery (MJ)
E_{Ash}	Energy due to ash (MJ)
E_{Flue}	Energy due to flue gas (MJ)
E_{Sen}	Energy due to sensible heating (MJ)
$E_{Unburnt}$	Energy due to unburnt (MJ)
η_{energy}	Energy efficiency (%)
E_{Evap}	Energy for evaporating water (MJ)
$E_{Wall-loss}$	Energy lost through wall (MJ)
Ex_{dest}	Exergy destruction (MJ)
$Ex_{Wall-loss}$	Exergy due to heat lost through wall (MJ)
η_{exergy}	Exergy efficiency (%)
Ex_{In}	Exergy input (MJ)
Ex_{Air}	Exergy of air (MJ)
Ex_{bag}	Exergy of bagasse (MJ)
$Ex_{Chemicals}$	Exergy of chemicals (MJ)
Ex_{Fr}	Exergy of floating residue (MJ)
Ex_{Flue}	Exergy of flue gas (MJ)
Ex_{Juice}	Exergy of juice (MJ)
Ex_{Vapour}	Exergy of water vapour (MJ)
Ex_{out}	Exergy output (MJ)
G_k	Generation of turbulent kinetic energy
T_i	Initial juice temperature (K)
T_0	Initial temperature (K)
h_{fg}	Latent heat of vaporization of water (kJ/kg)
$m_{bagasse}$	Mass of bagasse (kg)
m_{Flue}	Mass of flue gas (kg)
$m_{Jaggery}$	Mass of jaggery (kg)

m_{juice}	Mass of juice (kg)
m_{wv}	Mass of water (kg)
m_{wv}	Mass of water evaporated (kg)
L_m	Mean optical path length (m)
NCV	Net calorific value (kJ/kg)
$I(\vec{r}, \vec{s})$	Radiant intensity at position $\vec{r}$ in the direction of $\vec{s}$ $\left(\frac{W}{m^2.sr}\right)$
σ_s	Scattering coefficient
h_0	Specific enthalpy at ambient temperature (kJ/kg)
h	Specific enthalpy of water vapour (kJ/kg)
S_0	Specific entropy at ambient temperature (kJ/kgK)
S	Specific entropy of water vapour (kJ/kgK)
C_{pjagg}	Specific heat of jaggery (J/kgK)
C_{pw}	Specific heat water (J/kgK)
$EX_{ch.CO_2}$	Standard chemical exergy of carbon dioxide (kJ/mol)
$EX_{ch.N_2}$	Standard chemical exergy of nitrogen (kJ/mol)
$EX_{ch.H_2O}$	Standard chemical exergy of water vapour (kJ/mol)
$\hat{\Gamma}_g$	Stress tensor in gaseous phase
T_s	Striking temperature of jaggery (K)
T_{flue}	Temperature of flue gas (K)
ε_T	Total emissivity
ε_g	Turbulent dissipation rate in gaseous phase
$C_{1\varepsilon}$ and $C_{2\varepsilon}$	Turbulence model constants
η_k	Turbulent Prandtl number for kinetic energy
μ_t	Turbulent viscosity
v_g	Velocity vector in gaseous phase

Symbols

a	Absorption coefficient
u	Average velocity
ρ	Density

Δ	Difference
η	Efficiency
k	Thermal conductivity
$\emptyset$	Ratio of the chemical exergy to the net calorific value
φ	Source term

Abbreviations

APEDA	Agricultural & processed food products export development authority
ATC	Automatic temperature compensation
BSS	British standard sieve
CV	Calorific value
CO ₂	Carbon dioxide
CO	Carbon monoxide
CFD	Computational fluid dynamics
DN	Depletion number
EBI	Environmental benign index
EDI	Environmental degradation Index
EDC	Environmental destruction coefficient
GVA	Gross value added
HTC	Heat transfer coefficient
HTF	Heat transfer fluid
HCV	Higher calorific value
IR	Infrared radiation
MOSPI	Ministry of statistics and programme implementation
MT	Million ton
MP	Modified plant
NCV	Net calorific value
NO _x	Nitrogen oxides
NCS	Non-centrifugal cane sugar
NWER	Non-reusable waster exergy ratio
PM	Particulate matter
PMFME	Pradhan Mantri formalization of micro food processing enterprises
RTE	Radiative transfer equation

RTD	Resistance temperature detector
RANS	Reynolds-Averaged Navier-Stokes
SH	Slot hole
SO ₂	Sulphur dioxide
SO _x	Sulphur oxides
SI	Sustainability index
UDF	User defined function
WER	Waste exergy ratio
WSGGM	Weighted sum grey gas model