

**APPLICATION AND UTILIZATION OF
THERMOELECTRIC GENERATOR FOR A BIOMASS
COOKSTOVE**

RISHA MAL



**CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

October 2018

©Indian Institute of Technology Delhi (IITD), New Delhi, 2018

**APPLICATION AND UTILIZATION OF
THERMOELECTRIC GENERATOR FOR A BIOMASS
COOKSTOVE**

by

RISHA MAL

CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY

Submitted

In the fulfilment of the requirement of the degree of Doctor of Philosophy



INDIAN INSTITUTE OF TECHNOLOGY DELHI

October 2018

Dedicated to my Daughter

Adrita

CERTIFICATE

This is to certify that thesis titled “**APPLICATION AND UTILIZATION OF THERMOELECTRIC GENERATOR FOR A BIOMASS COOKSTOVE**” being submitted by **MS. RISHA MAL** to the Indian Institute of Technology Delhi for the award of degree **DOCTOR OF PHILOSOPHY** in Engineering/Technology is a record of original bonafide research work carried out by her under our guidance and supervision. In our opinion, the thesis has reached the standard of fulfilling the requirements of all the regulations related to the degree. The research report and results presented in this thesis have not been submitted, in part or in full, to any other university or institution for the award of any degree or diploma.

This is also certified that she has pursued the prescribed course of research.

Prof. (Emeritus) Rajendra Prasad
Centre for Rural Development and Technology
Indian Institute of Technology Delhi
New Delhi – 110016, India.

Prof. Virendra Kumar Vijay
Centre for Rural Development and Technology
Indian Institute of Technology Delhi
New Delhi – 110016, India.

ACKNOWLEDGEMENTS

I would like to acknowledge the support of and extend my gracious thanks to several individuals who have contributed in more ways than one in helping me complete this arduous journey. From scoping my research work all the way to helping me put the finishing touches to my thesis, they have lent invaluable support to the various aspects of my dissertation.

At the outset, I would like to express my sincere gratitude for the immense amount of encouragement I have received from both of my research supervisors, Prof. Rajendra Prasad and Prof. Virendra Kumar Vijay of the Centre for Rural Development and Technology, Indian Institute of Technology Delhi. Their tutelage has been more than inspirational. Their guidance at every stage of my doctoral research, from choosing the relevant pre-requisite courses to preparing me for my comprehensive examination, providing the necessary facilities for my experiments, reviewing my research publications, helping me with my synopsis and right upto shaping my thesis and dissertation, has been invaluable. I am extremely indebted to them for their patience and dedication in extending support to me.

I would like to express my sincere thanks to Prof. Sukumar Mishra of Department of Electrical Engineering, Indian Institute of Technology Delhi for his advice and support. My gratitude to Prof. Satyawati Sharma and Prof. S. N. Naik, Centre for Rural Development and Technology (CRDT), Indian Institute of Technology Delhi for their kind support and motivation.

I am also deeply indebted to other members of faculty at CRDT, in particular Dr. Anushree Malik, Prof. Santosh Satya, Dr. Hari Prasad for their help and feedback from time to time.

I am immensely grateful to Mr. Amit Ranjan Verma and Mr. Ratnesh Tiwari of CRDT, IIT Delhi for helping me with my research work, sharing concepts, constant motivation and other support in managing this challenging endeavour. Research would have been a dull journey had it not been for these brainstorming discussions on the IIT Delhi campus.

I am deeply grateful to Mr Birendra Singh, Workshop help at CRDT, IIT for his tremendous support in designing my experimental setup. My sincere appreciation for the help from Ms. Manju, Mr. Ramesh and Ms. Sushmita Dass who have helped me in the management of my laboratory work.

I would like to express my heartfelt gratitude to my parents and family for their constant encouragement, support and affection throughout my life and making me who I am. I thank my husband for being my backbone and extending support in emotional and professional front. I am also grateful to all those who helped me directly or indirectly in taking my research work to completion.

The financial support that was received from IIT Delhi, Government of India to carry out this research work is gratefully acknowledged.

And then, I repose my deep faith in Almighty God who continues to watch over me despite my many imperfections and I humbly seek His continued benevolence and blessings.

RISHA MAL

ABSTRACT

About 70% population of a developing country like India resides in rural areas and from those about 78% of them use biomass for cooking. The traditional biomass cookstoves are being used in such developing countries for the cooking needs. The burning of biomass increases health hazards due to emissions of harmful pollutants which also contribute to climate change.

Compared to a traditional biomass cookstove, a forced draft biomass cookstove can reduce polluting emissions to a considerable level. To achieve cleaner combustion the forced draft stoves are provided with a small fan. The household need to be connected with grid electricity to run the electric fan or with a battery. Many of the rural households do not have access to electricity. The requirement of this small quantity of electricity in such off-grid areas can be fulfilled by deploying an innovative, novel and sustainable technology in conjunction with a biomass cookstove, a Thermo Electric Generator (TEG). A TEG Stove can be used for cooking as well as some electricity generation from waste heat of the stove.

The thermoelectric generators modules are mainly made of semiconductor materials like Bismuth Telluride (Bi_2Te_3). Various types of thermoelectric generators are commercially available in the market.

A TEG stove could, thus, make a cleaner combustion as well as light an LED lamp (or charge a mobile phone battery) simultaneously. To achieve the adequate electricity

generation from TEG, different electrical topologies have been discussed and an appropriate one selected.

The laboratory testing of a TEG stove developed was turned to give a much better performance as compared to traditional cookstoves. The prototype developed is rather costly, INR 9000. The TEG cookstove manufacturing could be commercialized for off-grid rural areas. Scaling up the manufacturing in India may also lead to cost reduction of TEG stoves. Extensive field testing on these cookstoves for its performance has to be established.

सार

भारत जैसे विकासशील देश की लगभग 70% आबादी ग्रामीण क्षेत्रों में रहती है और उनमें से 78% खाना पकाने के लिए बायोमास का उपयोग करती हैं। खाना पकाने की जरूरतों के लिए ऐसे विकासशील देशों में पारंपरिक बायोमास cookstoves का उपयोग किया जा रहा है। बायोमास जलने से हानिकारक प्रदूषण के उत्सर्जन के कारण स्वास्थ्य के खतरे बढ़ जाते हैं जो जलवायु परिवर्तन में भी योगदान देते हैं।

पारंपरिक बायोमास कुकस्टोव की तुलना में, एक मजबूर मसौदा बायोमास कुकस्टोव प्रदूषण उत्सर्जन को काफी स्तर तक कम कर सकता है। क्लीनर दहन प्राप्त करने के लिए मजबूर मसौदे स्टोव को एक छोटे प्रशंसक के साथ प्रदान किया जाता है। बिजली के प्रशंसक या बैटरी के साथ घर को ग्रिड बिजली से जोड़ा जाना चाहिए। ग्रामीण परिवारों में से कई को बिजली तक पहुंच नहीं है। ऐसे ऑफ-ग्रिड क्षेत्रों में बिजली की इस छोटी मात्रा की आवश्यकता को बायोमास इलेक्ट्रिक जेनरेटर (टीईजी) के बायोमास कुकस्टोव के संयोजन के साथ एक अभिनव, उपन्यास और टिकाऊ तकनीक को तैनात करके पूरा किया जा सकता है। एक टीईजी स्टोव का इस्तेमाल स्टोव के अपशिष्ट गर्मी से खाना पकाने के साथ ही कुछ बिजली उत्पादन के लिए किया जा सकता है।

थर्मोइलेक्ट्रिक जेनरेटर मॉड्यूल मुख्य रूप से अर्धचालक पदार्थों जैसे बिस्मुथ टेलुराइड से बने होते हैं। विभिन्न प्रकार के थर्मोइलेक्ट्रिक जेनरेटर वाणिज्यिक रूप से बाजार में उपलब्ध हैं।

इस प्रकार, एक टीईजी स्टोव एक क्लीनर दहन के साथ-साथ एलईडी लैंप (या मोबाइल फोन बैटरी चार्ज) को एक साथ ला सकता है। पर्याप्त बिजली प्राप्त करने के लिए टीईजी से पीढ़ी, विभिन्न विद्युत टोपोलॉजी पर चर्चा की गई है और एक उपयुक्त चुना गया है।

पारंपरिक कुकस्टोव की तुलना में विकसित एक टीईजी स्टोव का प्रयोगशाला परीक्षण एक बेहतर प्रदर्शन देने के लिए बदल दिया गया था। विकसित प्रोटोटाइप महंगा है, INR 90000. टीईजी कुकस्टोव विनिर्माण ऑफ-ग्रिड ग्रामीण क्षेत्रों के लिए व्यावसायीकरण किया जा सकता है। भारत में विनिर्माण को बढ़ाकर टीईजी स्टोव की लागत में कमी आ सकती है। अपने प्रदर्शन के लिए इन cookstoves पर व्यापक क्षेत्र परीक्षण स्थापित किया जाना है।

CONTENTS

CERTIFICATE	i
ACKNOWLEDGMENTS	ii
ABSTRACT	v
LIST OF CONTENT	vii
LIST OF FIGURES	xi
LIST OF TABLES	xviii
NOMENCLATURE	xix
CHAPTER 1– INTRODUCTION	1
1.1 Renewable energy metrics	1
1.2 Cooking energy scenario.....	2
1.2.1 Problem statement.....	10
1.3 Scope of Work	11
1.4 Aim of present research work	11
1.5 Objectives	13
1.6 Organization of the Thesis	13
CHAPTER 2 - LITERATURE REVIEW	15
2.1 Physics of thermoelectricity.....	15
2.1.1 History of thermoelectric	15
2.1.2 Performance parameters of thermoelectric generator	16
2.1.2.1 The Seebeck coefficient.....	16
2.1.2.2 The Figure of Merit (Z).....	17

2.1.2.3	The conversion efficiency and current.....	18
2.1.2.4	The maximum power efficiency	19
2.1.2.5	Thermoelectric materials	19
2.2	Applications of thermoelectrics	28
2.2.1	Refrigeration	28
2.2.2	Power generation	29
2.2.2.1	DC-DC converter	30
2.4.2.2	Battery Charging.....	30
2.3	Construction of TEG.....	33
2.3.1	Thermocouple construction	33
2.3.2	Thermoelectric contacts	37
2.3.3	Thermocouple configuration.....	39
2.3.4	Thermal insulation	43
2.3.5	Interface materials.....	43
2.3.6	Consistency and degradation of TE module	46
2.4	Prior TEG cookstove researches.....	50
2.5	Summary	57
 CHAPTER 3 - STOVE COMPONENTS CONSTRUCTION AND TESTING		59
3.1	Material selection.....	59
3.2	Stove components and construction.....	60
3.3	TEG Unit.....	65
3.3.1	Module testing and selection	66
3.3.1.1	TEC12710 (Peltier module).....	66

3.3.1.2 HZ-14 (Seebeck module).....	70
3.3.1.3 HZ-9 (Seebeck module).....	77
3.3.1.4 Comparison between HZ-14 and HZ-9.....	83
3.3.1.5 TG12-8 (Seebeck module).....	87
3.3.2 Heat sink	91
3.3.3 Cooling of the TEG.....	93
3.3.3.1 Air cooled forced convection.....	93
3.3.4 Heat side plate.....	95
3.3.5 Electronics.....	95
3.4 Summary	96
CHAPTER 4 – EXPERIMENTS AND RESULTS.....	97
4.1 Performance of cold side heat sink	97
4.2 Performance of heat side plate.....	102
4.3 Electrical Topologies	108
4.3.1 Battery operated electrical topology (Configuration 0).....	108
4.3.1.2 Lessons learnt from field.....	113
4.3.2 Battery operated electrical topology (Configuration 1).....	114
4.3.3 Non-battery operated electrical topology (Configuration 2)	123
4.3.3.1 Load conditions	126
4.3.3.2 Load with electronics and fan.....	127
4.3.3.3 Load with electronics, fan and LED light/Li-ion battery	129
4.4 The final Prototype	131
4.5 Summary	135

CHAPTER 5 - TESTING AND PERFORMANCE OF THE STOVE WITH DIFFERENT ELECTRICAL CONFIGURATIONS.....	138
5.1 Testing Protocol.....	138
5.1.1 Equipment and Accessories	138
5.1.2 Fuel and its preparation.....	143
5.1.3 Burning rate capacity	144
5.1.4 Procedure	145
5.2 Testing parameters	147
5.2.1 Thermal efficiency.....	147
5.2.2 Power output rating.....	147
5.2.3 Fuel Burning Rate.....	147
5.2.4 Standards.....	148
5.3 Results.....	148
5.4 Cost Estimates.....	154
CHAPTER 6 - CONCLUSION AND FUTURE PROSPECTS.....	156
5.1 Conclusion	156
5.2 Future prospects	160
REFERENCES.....	161
ANNEXURE – I (DATA RELATED TO CHAPTER 3).....	174
ANNEXURE – II (DATA RELATED TO CHAPTER 4)	217
LIST OF PUBLICATIONS	227
BRIEF CURRICULAM VITAE	233

LIST OF FIGURES

Figure 1.	Total energy consumption 2010	1
Figure 2.	Global and regional trends in population relying on solid fuels as the main cooking fuel	2
Figure 3.	Total deaths due to HAP regionally in 2012	3
Figure 4.	World Clean Cooking Access and Lack of Access by Region	4
Figure 5.	Cooking in traditional mud stove	5
Figure 6.	Biomass contributing to global heat and electricity generation.....	6
Figure 7.	Thermal conductivity, electrical conductivity and Seebeck coefficient of P-type and N-type carrier concentration	17
Figure 8.	Basic DC-DC boost converter	30
Figure 9.	Stages of charging a li-ion battery	32
Figure 10.	Single stage TEG with two thermocouple	34
Figure 11.	(a) Sandwich arrangement of TE material (b) TE FOM of a sandwich arrangement	35
Figure 12.	Segmented arrangement of TEM	36
Figure 13.	Arrangement of junctions in a TEG module.....	40
Figure 14.	Direction of flow of current with temperature gradient	41
Figure 15.	Voltage and power curve in comparison to current of a operated at a ΔT of 220 °C	41
Figure 16.	The junction quality factor as compared to clamping force for different interface material	44

Figure 17.	Effect of alternating current resistance as compared to number of thermal cycles	47
Figure 18.	Effect of alternating current resistance as compared to number of thermal cycles.....	48
Figure 19.	Effect of alternating current resistance as compared to time at 160°C.....	48
Figure 20.	Effect of figure of merit as compared to time at 160°C.....	49
Figure 21.	Effect of alternating current resistance operating at 100°C	50
Figure 22.	Wood Stove with Generator at Left Rear	51
Figure 23.	EgoFagao stove integrated with TEG by Mastbergen in 2007	52
Figure 24.	Commercial Biolite camp stove and Home stove	54
Figure 25 (a)	Enhanced commercial stove and add-on design: (i) Envirofit “rocket” commercial stove with RTI add-on and (ii) RTI TECA design for a continuous feed biomass stove.....	54
Figure 25 (b)	Testing of TECA device with commercial Envirofit stove. (A) Photo of RTI prototype stove being tested at the EPA - note measurement equipment setup to record TE power generation and blower power use. (Bi) Comparison of cookstove test results including RTI TECA enhancement to Envirofit stove	54
Figure 26.	A natural draft μ Power Stove Generator with a thermoelectric generator (TEG)	55
Figure 27.	Comparison of PM and CO emissions from 3-stone fir, StoveTech-Rocket, StoveTech-Rocket with TEG fan and skirt and Phillips stove under a variety of conditions	55

Figure 28.	Inner combustion chamber	60
Figure 29.	Bottom view and Top view of mould	61
Figure 30.	Front and back of air jacket	62
Figure 31.	Outer chamber and duct	63
Figure 32.	Pan support of the cookstove	63
Figure 33.	Computer aided design of front and top view of the TEG cookstove	64
Figure 34.	Computer aided design (CAD) representation of the TEG cookstove	65
Figure 35.	Setup for testing TE modules.....	67
Figure 36.	Temperature difference and load voltage in natural draft condition.....	68
Figure 37.	Temperature difference and load voltage, initially in natural draft condition and later when the power of the module drives the fan and runs in forced draft condition.....	69
Figure 38.	Load voltage and Power generated by TEG using a 0.5W fan.....	69
Figure 39.	Characteristic of power versus load resistance of HZ-14 at ΔT 200°C	74
Figure 40.	Characteristic of load current versus voltage of HZ-14 at ΔT 200°C.....	74
Figure 41.	Characteristic of load current versus Power of HZ-14 in y axis and efficiency in secondary y axis at ΔT 200°C.....	75
Figure 42.	Comparison of rise in load voltage as compared to rise in ΔT	76
Figure 43.	Comparison of rise in power as compared to rise in ΔT	76
Figure 44.	Comparison of power vs. voltage at different temperature difference	77
Figure 45.	Characteristic of power with load resistance of HZ-9 at ΔT 200°C	81
Figure 46.	Characteristic of load current with voltage of HZ-9 at $\Delta T=200^{\circ}\text{C}$	81

Figure 47.	Characteristic of load current with Power of HZ-9 in y axis and efficiency in secondary y axis at $\Delta T=200^{\circ}\text{C}$	82
Figure 48.	Comparison of power vs. voltage at different temperature difference	83
Figure 49.	Comparison of rise in power as compared to rise in ΔT	83
Figure 50.	Comparison of open-circuit voltage with respect to temperature difference between HZ-9 and HZ-14	83
Figure 51.	Comparison of load voltage with respect to temperature difference between HZ-9 and HZ-14	85
Figure 52.	Comparison of temperature difference with internal resistance between HZ-9 and HZ-14	85
Figure 53.	Comparison of heat flow within the module with respect to temperature difference between HZ-9 and HZ-14	86
Figure 54.	Comparison of heat flow within the module with respect output power between HZ-9 and HZ-14	86
Figure 55.	Comparison of power per module with respect to temperature difference between HZ-9 and HZ-14	87
Figure 56.	Performance of TG12-8 with varying hot side temperature on secondary x-axis with heat on x-axis, optimum power in y-axis and optimum voltage in secondary y-axis at constant cold side temperature of 50°C	89
Figure 57.	Performance of TG12-8 with varying hot side temperature on secondary x-axis with heat on x-axis, optimum power in y-axis and optimum voltage in secondary y-axis at constant cold side temperature of 100°C	89
Figure 58.	Benchmark testing of TEG and heat sink	91

Figure 59.	Performance measurement setup for TEG	92
Figure 60.	Vertical fin, flower fin, extended flower fin, pin fin heat sink	94
Figure 61.	Vertical fin heat sink	97
Figure 62.	Flower fin heat sink	98
Figure 63.	Extended flower fin heat sink	98
Figure 64.	Pin fin heat sink	99
Figure 65.	Comparison of different heat sinks by natural draft with HZ-9 TEG module.....	100
Figure 66.	Comparison of heat sink by forced draft with HZ-9 module.....	101
Figure 67.	Comparison of heat sink in forced draft enclosed within a duct with one side opening with HZ-9 module	102
Figure 68.	Heat plate aluminium metal block	104
Figure 69.	Thin stainless steel heat plate with single stainless steel probes	104
Figure 70.	Copper heat plate with four copper probes	105
Figure 71.	Heat plate of thin aluminium plate with five cyl. aluminium probes	105
Figure 72.	Heat plate with stainless steel plate with five cylindrical stainless steel probes inserted inside the plate	107
Figure 73.	Comparison of heat plate metal and design with respect to time and open-circuit voltage of TEG	108
Figure 74.	Configuration 1 (a) Battery charging circuit by TEG (b) Fan driving circuit (battery discharging end)	109
Figure 75.	(i) 5V DC-DC step-up converter, (ii) 12 V DC-DC step-up converter, (iii) integrated circuit box	110

Figure 76.	Arrangement of the various components in the TEG fitted cookstove....	111
Figure 77.	Load voltage was plotted with respect to time of configuration 0 for six tests	111
Figure 78.	Comparison of temperature difference was plotted with respect to time of configuration 0 for six tests.....	112
Figure 79.	Comparison of time as compared to power of configuration 0	112
Figure 80.	The actual use of TEG cookstove in field.....	114
Figure 81.	1.5-12 V step up converter and 3-5 V step up converter	115
Figure 82.	Circuit box for TEG	115
Figure 83.	Configuration 1 of battery operated TEG stove.....	116
Figure 84.	Step-wise functional path of power flow in the configuration 1	120
Figure 85.	Load voltage with time of configuration 1	122
Figure 86.	Temperature difference with time of configuration1	122
Figure 87.	Power with time of configuration 1	123
Figure 88.	Configuration 2 for running fan and battery charging simultaneously with TEG power.....	124
Figure 89.	Temperature difference with respect to time	126
Figure 90.	Load voltage versus time	127
Figure 91.	Load current versus load voltage	128
Figure 92.	Power versus time	128
Figure 93.	Black marker shows the start of fan, red marker shows the range of running fan only, and green marker shows the running of fan and lighting of LED simultaneously with the power of TEG	130

Figure 94.	Power versus time	130
Figure 95.	Time vs. temperature difference of TEG	131
Figure 96.	Load current with load voltage of six tests for five TEG cookstoves.....	133
Figure 97.	Power with time of six tests for five TEG stovesc	135
Figure 98.	Design setup for stove testing.....	143
Figure 99.	Thermal efficiency of different electrical config. with its TEGs	148
Figure 100.	Power output of different electrical configuration with its TEGs	149
Figure 101.	Particulate matter of different electrical configuration with its TEGs.....	149
Figure 102.	Carbon monoxide of different electrical config. with its TEGs.....	150
Figure 103.	Thermal efficiency of configuration 2 with TG12-8 of five TEG cookstoves.....	151
Figure 104.	Power output of configuration 2 with TG12-8 of five TEG stoves	152
Figure 105.	Particulate matter of configuration 2 with TG12-8 of five TEG cookstoves	152
Figure 106.	Carbonmono oxide of configuration 2 with TG12-8 of five TEG cookstoves.....	153
Figure 107.	Body temperature of configuration 2 with TG12-8 of five TEG cookstoves	153

LIST OF TABLES

Table 1.	The thermoelectric properties of different semiconductors	22
Table 2.	Comparison of different rechargeable batteries	31
Table 3.	Charging characteristics of a li-ion battery	33
Table 4.	TECA device electric power summary	54
Table 5.	Author Name, year and name of Stove of TEG cookstove researches	56
Table 6.	Raw materials for the design of the TEG cookstove	59
Table 7.	The thermal and electrical properties of HZ-14	70
Table 8.	Characteristics of HZ-14	71
Table 9.	Output parameters of HZ-14 at a ΔT of 200°C	72
Table 10.	The thermal and electrical properties of HZ-9	78
Table 11.	Characteristics of HZ-9.....	78
Table 12.	Output parameters of HZ-9 at a ΔT of 200°C	79
Table 13.	The thermal and electrical properties of TG12-8.....	88
Table 14.	The thermal and electrical properties of HZ-14, HZ-9 and TG12-8 at different ΔT	90
Table 15.	Aluminium vessels for thermal efficiency test	139
Table 16.	Cookstove standard performance parameters	148
Table 17.	Cost of the stove and TEG, HZ-9	154
Table 18.	Cost of the stove and TEG, TG1208-1LS.....	155
Table 19.	Comparison of different configurations with respect to electrical and stove testing parameters	159

NOMENCLATURE

α	Seebeck coefficient	V/°C
Z	figure of merit	dimensionless
T_H	hot side temperature	°C
T_C	cold side temperature	°C
Σ	electrical conductivity	$\Omega^{-1}\text{cm}^{-1}$
k	thermal conductivity	W/cm°C
ρ	electrical resistivity	Ωcm
L	length of one thermo-electric leg	cm
A	cross-sectional area of one thermo-electric leg	cm
Q_H	Heat flow from hot side	W
Q_C	Heat flow from cold side	W
R_L	load resistance	Ω
I	current	A
P	power	W
η_c	conversion efficiency	%
V_{oc}	open circuit voltage	V
P_{max}	maximum power	W
I_{max}	maximum current	A
R_{int}	internal resistance	Ω
ΔT	Temperature difference	°C
w	mass of water in vessel	kg
W	mass of vessel with lid	kg

F	rate of consumption of fuel wood	kg/h
H_{fuel}	calorific value of wood (or solid fuel)	kJ/kg