

**PERFORMANCE CHARACTERIZATION OF
MICRO POROUS MEDIA BURNER FOR HEAT
OR POWER GENERATION**

AYUB AHMED JANVEKAR

UNIVERSITI SAINS MALAYSIA

2019

**PERFORMANCE CHARACTERIZATION OF MICRO POROUS MEDIA
BURNER FOR HEAT OR POWER GENERATION**

by

AYUB AHMED JANVEKAR

**Thesis submitted in fulfilment of the
requirements for the degree of
Doctor of Philosophy**

February 2019

ACKNOWLEDGEMENT

Alhamdulillah Rabbil 'Alamin. Above all, I thank Allah for giving me the will and steadfastness to do this work specifically and cope with the life generally. The love and prayers of my parents are specially acknowledged for being the constant inspiration during this challenge.

I would like to express my deepest gratitude to my supervisor, Prof. Ir Dr Mohd Zulkifly Abdullah for his invaluable support and guidance. It was a great opportunity to work under his supervision. I would also like to extend my appreciation to Prof. Dr. Zainal Arifin Ahmad and Dr. Aizat Abas who have guided me in porous media preparation and technical reviews, respectively.

I would like to acknowledge the Universiti Sains Malaysia for offering USM Fellowship. I heartily acknowledge my father, mother, elder brother and younger brother for their deep motivation and support throughout my doctoral programme. I heartily acknowledge my wife and daughter for ever ending support in best possible ways. My special thanks are due to my friends Dr. A K Ismail, Dr. Ahmed Hussien, Dr. Pramod Kumar and all colleagues who have helped me directly or indirectly during my candidature. Without those helps, this research would not have been successful.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vii
LIST OF FIGURES	ix
LIST OF ABBREVIATIONS	xiv
LIST OF SYMBOLS	xv
ABSTRAK	xvi
ABSTRACT	xvii
CHAPTER ONE: INTRODUCTION	
1.1 General Introduction	1
1.2 Problem Statement	3
1.3 Objectives of the study	5
1.4 Scope of the Study	5
1.5 Thesis overview	6
CHAPTER TWO: LITERATURE REVIEW	
2.1 Introduction	8
2.2 Environmental Impact	8
2.3 Preparation of foam porous media	9
2.4 Combustion reaction mechanism in porous media	11
2.5 Types of fuels used in porous media combustion	17
2.5.1 Gas porous media combustion	17
2.5.2 Liquid porous media combustion	19
2.6 Formation of NO _x and CO	20
2.7 Effect of exhaust gas emissions on environment	22
2.8 Application of porous media combustion	24
2.8.1 Meso and micro scale burners	26

2.8.2	Non premixed and premixed approach	29
2.8.3	Lean porous media combustion	31
2.9	Enhancing combustion using external additives	32
2.10	Burners with electric power generation	33
2.11	Optimization using design of experiments	38
2.12	Numerical analysis of porous media combustion	39
2.12.1	One dimensional approach	39
2.12.2	Two dimensional approach	40
2.12.3	Three dimensional approach	40
2.13	Summary	41

CHAPTER THREE: METHODOLOGY

3.1	Introduction	43
3.2	Layout of porous media burner system	44
3.3	Manufacturing of foam porous media for preheat zone	48
3.4	Arrangement of porous media	52
3.5	Experimental testing procedures	54
3.5.1	Fuel mixture	54
3.5.2	Temperature and emission profiles	55
3.5.3	Thermal efficiency calculation	58
3.6	Significance of external additives	59
3.7	Enabling power generation	61
3.7.1	Thermoelectric and Thermophotovoltaic cells	61
3.7.2	Standard and hybrid configurations	64
3.7.3	Testing with electronic device	66
3.8	Experimental error analysis	67
3.9	Design of experiments using RSM optimization	68
3.10	Numerical study of the burner model	72

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1	Introduction	77
4.2	Arrangement of porous media for dual layer framework	77
4.3	Variation of the flow rate	79
4.4	Generating surface and submerged flame in the reaction zone	81

4.5	Flame stabilization during porous media combustion	82
4.6	Performance analysis with foam type of reaction zone	84
4.6.1.	Variation in thickness of preheat layer	84
4.6.1.1.	Preheat layer with 5 mm thickness	85
4.6.1.2.	Preheat layer with 10 mm thickness	87
4.6.1.3.	Preheat layer with 15 mm thickness	90
4.6.2.	Thermal efficiency with three different thickness	92
4.6.3.	Significance of thermal images	93
4.6.4.	Effect of NO _x and CO during combustion	98
4.7	Performance analysis with ball type of reaction zone	100
4.7.1.	Effect of reaction layer height on temperature profile	100
4.7.2.	Variation in emission parameters	106
4.7.3.	Variation in thermal efficiency	109
4.8	Comparison between foam and ball type of reaction zone	110
4.9	Effect of low vegetable oil droplets size on reaction zone	111
4.9.1.	Temperature distribution under lean combustion	111
4.9.2.	Analysis of emission parameters	116
4.9.3.	Enhancement in thermal efficiency	119
4.9.4.	Microscopic study of porous media before and after combustion	120
4.10	Enabling electric power system	122
4.10.1.	Comparison between TE and TPV cells	123
4.10.2.	Assessment of standard and hybrid configurations	124
4.10.3.	Variation in power output	131
4.10.4.	Testing with electronic gadgets	133
4.11	Optimization of height between TE cells and reaction zone	134
4.11.1.	Outcomes of the central composite design	136
4.11.2.	Results from analysis of variance (ANOVA)	138
4.11.3.	Consequences of factors on the response parameters	140
4.11.4.	Optimization of experimental results	144
4.12	Numerical simulation of porous media burner	145
4.12.1.	Modelling using SolidWorks	145
4.12.2.	Meshing using workbench	146
4.12.3.	Analysis using ANSYS FLUENT	147
4.13	Comparison with other researchers	149

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS	151
5.1 Conclusions	151
5.2 Recommendations for future work	154
REFERENCES	156
APPENDICES	
Appendix A: Peclet number calculation	
Appendix B: Error analysis	
LIST OF PUBLICATIONS	

LIST OF TABLES

	Page
Table 2.1	Previous work carried out with PMB using gaseous fuels. 18
Table 2.2	Experimental work on burner using liquid fuels. 20
Table 2.3	Variation of NO _x and CO with PMBs 24
Table 2.4	Burners with premixed /non premixed type of combustion 30
Table 2.5	Burner under lean ER 32
Table 2.6	Research work carried out using biofuels 33
Table 2.7	Researcher work carried out using TE/TPV cells 37
Table 3.1	Device and materials used in experimental study 47
Table 3.2	Equipments and materials used to make porous media 50
Table 3.3	Porous media used in the experimental study 52
Table 3.4	Corresponding value of ER for fuel and air flow rate 55
Table 3.5	General specifications of sunflower oil 59
Table 3.6	Electric devices used for electric power system 61
Table 3.7	Circuit fan specifications 65
Table 3.8	Actual and coded values for the factor of CCD design 71
Table 4.1	Relation between flame type with respect to equivalence ratio 82
Table 4.2	Thermal efficiency at t = 5, 10 and 15mm. 92
Table 4.3	Percentage difference between experimental and thermal imager temperature on the burner wall 97
Table 4.4	Thermal efficiency with ball type of porous media 109
Table 4.5	Thermal efficiency at various ER with respect to VO droplets 119
Table 4.6	Results of the central composite design 137
Table 4.7	ANOVA of model for responses; Y1 and Y2 with the operating parameters A, B and C 139
Table 4.8	The validation of model response and experimental value 145

Table 4.9	Percentage difference between experimental and simulation values	149
Table 4.10	Comparison of similar study carried out in porous media burner.	150

LIST OF FIGURES

	Page
Figure 2.1 Schematic of the flow through porous media (Mohamad, 2005)	12
Figure 2.2 Schematic to highlight major heat transfer modes and directions.	13
Figure 2.3 Mechanisms of heat transfer in a PMB (Mohamad, 2005)	14
Figure 2.4 Meso scaled stainless steel burner a) Actual photograph, (b) 2D image representation main features (Singh et al., 2016).	27
Figure 2.5 Design feature of the micro combustor (Bani et al., 2018a)	28
Figure 2.6 Cogeneration thermoelectric system (Alanne et al., 2014)	36
Figure 2.7 Experimental setup (Mustafa, 2016a)	37
Figure 3.1 Burner housing; (a) line diagram and (b) actual image	44
Figure 3.2 Arrangement of burner components. (1) Burner housing, (2) K - type temperature thermocouple, (3) Combustion fuel gas analyser, (4) Gas collector, (5) Mixing unit, (6) Pre-mix unit, (7) Digital air flow controller, (8) Digital butane gas flow controller, (9) Butane cartridge, (10) Air pump, (11) Data acquisition system	45
Figure 3.3 Actual photographic image of the burner setup	46
Figure 3.4 Details on the preparation of porcelain porous media	49
Figure 3.5 Preparation of foam PM; (a) mixing of binder with distilled water, (b) mixing of slurry, (c) pre-set rollers to remove excess slurry and (d) final template	51
Figure 3.6 Ceramic materials, (a) Alumina foam, (b) Porcelain foam, (c) Alumina sphere and (d) Zirconia sphere	53
Figure 3.7 (a) Arrangements of thermocouples and (b) DAQ	56
Figure 3.8 (a) Infrared thermometer (b) Thermal imager and (c) Surface probe	56
Figure 3.9 (a) Portable gas analyser and (b) Gas collector	57
Figure 3.10 Researcher work carried out using VO	60
Figure 3.11 (a) Actual TE cells and (b) Working principle of TE cells	62

Figure 3.12	(a) Actual TPV cells and (b) Dimensions of TPV cell	63
Figure 3.13	Circuit diagram to measure current and voltage	63
Figure 3.14	(a) Solar panel with four solar cells and (b) Circuit fan	64
Figure 3.15	Configurations; (a) standard and (b) hybrid	65
Figure 3.16	Configurations: (a) One cell standard , (b) One cell hybrid, (c) Four cell standard and (d) Four cell hybrid	66
Figure 3.17	USB module	67
Figure 3.18	Flow chart for design of experiments	69
Figure 3.19	RSM optimization using central composite design	71
Figure 3.20	Porous media burner computational domain	73
Figure 4.1	Reaction zone – Preheat zone (a) Alumina foam – porcelain foam, (b) Alumina ball – porcelain foam and (c) Zirconia ball – porcelain foam	78
Figure 4.2	Temperature profiles at different fuel flow rate of foam porous media with various thickness of reaction zone	79
Figure 4.3	Temperature profiles at different fuel flow rate of alumina ball PM with various thickness of reaction zone.	80
Figure 4.4	Temperature profiles at different fuel flow rate of zirconia ball PM with various thickness of reaction zone	80
Figure 4.5	Variation of flame temperature with time (surface flame)	83
Figure 4.6	Variation of average wall temperature with time (surface flame)	83
Figure 4.7	Variation of flame temperature with ER at preheat layer of 5mm	85
Figure 4.8	Variation of average wall temperature with ER at preheat layer of 5, 10 and 15mm.	86
Figure 4.9	Variation of flame temperature with ER at preheat layer of 10mm	88
Figure 4.10	With foam porous media in reaction zone at ER=0.7; (a) surface flame with preheat layer of 10 mm and (b) submerged flame with preheat layer of 10 mm (a) surface flame with preheat layer of 15 mm and (b) submerged flame with preheat layer of 15 mm	90

Figure 4.11	Variation of flame temperature with ER at preheat layer of 15mm	91
Figure 4.12	Maximum wall temperature with preheat layer of 5mm (surface flame)	94
Figure 4.13	Maximum wall temperature with preheat layer of 10mm (surface flame)	94
Figure 4.14	Maximum wall temperature with preheat layer of 15mm (surface flame)	95
Figure 4.15	Variation in burner wall temperature with preheat layer of 10mm (submerged flame)	95
Figure 4.16	Variation in burner wall temperature with preheat layer of 15mm (submerged flame)	96
Figure 4.17	Top view showing variation in temperature during submerged flame with preheat layer of 10mm	96
Figure 4.18	Interdependency of NO _x (ppm) concentration with ER	98
Figure 4.19	Interdependency of CO (ppm) concentration with ER	99
Figure 4.20	Temperature profile with 10mm reaction zone	101
Figure 4.21	Temperature profile with 20mm reaction zone	101
Figure 4.22	Temperature profile with 30mm reaction zone	102
Figure 4.23	Average wall temperature with alumina ball type of PM	103
Figure 4.24	Average wall temperature with zirconia ball type of PM	104
Figure 4.25	Flame with ball alumina in reaction zone ; (a) surface flame and (b) submerged flame	105
Figure 4.26	Flame with ball zirconia in reaction zone ; (a) surface flame and (b) submerged flame	106
Figure 4.27	Deviation of NO _x (ppm) with alumina ball porous media	107
Figure 4.28	Deviation of NO _x (ppm) with zirconia porous media	107
Figure 4.29	Deviation of CO (ppm) with alumina porous media	108
Figure 4.30	Deviation of CO (ppm) with alumina zirconia porous media	108
Figure 4.31	Temperature distribution with 20 μ L of VO	113
Figure 4.32	Temperature distribution with 40 μ L of VO	113

Figure 4.33	Temperature distribution with 60 μL of VO	114
Figure 4.34	Temperature distribution with 80 μL of VO	114
Figure 4.35	Deviation in surface flame temperature with and without VO	115
Figure 4.36	Deviation in wall temperature with and without VO	115
Figure 4.37	Interdependency of NO _x with ER	117
Figure 4.38	Interdependency of CO with ER	118
Figure 4.39	SEM image of alumina foam PM before combustion	121
Figure 4.40	SEM image of alumina foam PM after combustion	121
Figure 4.41	XRD plot of reaction porous media	122
Figure 4.42	Variation of voltage across various ER for TE and TPV cells	123
Figure 4.43	Variation of current across various ER for TE and TPV cells	124
Figure 4.44	Variation of average temperature on the surface of solar panel	125
Figure 4.45	Variation of power output from the solar planes with respect to time	126
Figure 4.46	Variation of average velocity of circuit fan with time	127
Figure 4.47	Variation of voltage against ER with single TE cell arrangement	128
Figure 4.48	Variation of voltage against ER with quad TE cell arrangement	128
Figure 4.49	Variation of current against ER with single TE cell arrangement	129
Figure 4.50	Variation of current against ER with quad TE cell arrangement	129
Figure 4.51	Variation of power against ER with single TE cell arrangement	132
Figure 4.52	Variation of power against ER with quad TE cell arrangement	132
Figure 4.53	Pictorial representation of independent variable (height); (a) 50mm, (b) 100 and (c)150mm	136
Figure 4.54	Perturbation plot for surfaces flame temperature	141
Figure 4.55	Perturbation plot for voltage	141
Figure 4.56	Perturbation plot for current	142

Figure 4.57	Three dimensional response surface and contour plots for temperature	142
Figure 4.58	Three dimensional response surface and contour plots for voltage	143
Figure 4.59	Three dimensional response surface and contour plots for current	143
Figure 4.60	Three dimensional view of burner assembly in side view	146
Figure 4.61	Variations in surface flame temperature (°C)	148
Figure 4.62	Variations in NO _x (ppm)	148
Figure 4.63	Variations in CO (ppm)	149

LIST OF ABBREVIATIONS

ER	Equivalence ratio
VO	Vegetable oil
CAD	Computer Aided Design
CFD	Computational fluid dynamics
CO	Carbon monoxide
LPG	Liquid petroleum gas
LPM	Litre per minute
NO	Nitrogen oxide
PMC	Porous media combustion
PMB	Porous media burners
PM	Porous media
SEM	Scanning electron microscopy
TE	Thermoelectric
TPV	Thermophotovoltaic
UDF	User-defined functions
UHC	Unburned hydrocarbons
USM	Universiti Sains Malaysia
XRD	X-ray diffraction
USB	Universal Serial Bus
DAQ	Data acquisition
AF_S	Stoichiometric air fuel ratio
AF_a	Actual air–fuel ratio

LIST OF SYMBOLS

C_w, C_p	specific heat of water and the container (J/kg-K)
t	Thickness of preheat layer (mm)
h	Height of the reaction layer (mm)
Pe	Peclet number
F	Laminar flame speed (m/s)
D	Equivalent diameter (m)
ρ	Density of the gas mixture (kg/m ³)
k	Thermal conductivity (W/mK)
r	Radius (m)
T	Temperature (°C)
t	Time (s)
Q_{in}	Energy supplied from butane (kW)
Q_{out}	Energy generated from combustion (kW)
V_f	Volumetric flowrate (kg/m ³)
M_f	Mass flow rate (kg/s)
n_{th}	Thermal efficiency
M_w	Mass of water (kg)
T_i	Initial temperature (°C)
t'	Time (s)
\bar{x}	Mean value
σ_x	Standard deviation
$\sigma_{\bar{x}}$	Standard error

CIRI PRESTASI PEMBAKAR MIKRO MEDIA BERLIANG UNTUK PENGHASILAN HABA ATAU KUASA

ABSTRAK

Ancaman kehabisan bahan api mempengaruhi ekonomi negara. Oleh itu, beberapa usaha dibuat untuk menambah baik penggunaan bahan api dengan mencipta pembakar yang lebih efisien. Oleh yang demikian, kajian ini berfokus untuk membina pembakar mikro media berliang berasaskan butana. Pembakar ini direka bentuk untuk menjalani pembakaran permukaan dan tenggelam dengan nisbah setara. Dua jenis lapisan reaksi diuji; media berliang jenis buih dan bola, manakala busa tembikar di zon pra pemanas. Ketebalan tindak balas dan lapisan pra pemanas diubah untuk mendapatkan prestasi pembakaran yang optimum. Oleh itu, kecekapan haba 90% telah dicatatkan dengan menggunakan busa alumina 15 mm bersama-sama dengan busa tembikar 10 mm. Nilai NO_x dan CO pada nisbah setara yang optimum adalah kurang daripada 15 dan 60 ppm. Tambahan pula, peningkatan 4% dalam kecekapan haba dicapai dengan menambahkan titisan minyak sayur-sayuran sebanyak 80µL ke atas lapisan reaksi. Di samping itu, kuasa elektrik 2.018 W dihasilkan dari pembakaran permukaan menggunakan sel TE. Sel-sel TE ini disepadukan dengan konfigurasi hibrid, termasuk kipas litar yang dikuasakan oleh panel solar. Selain itu, ketinggian antara lapisan reaksi dan sel TE dioptimumkan (69 mm) menggunakan reka bentuk eksperimen untuk meningkatkan lagi kuasa elektrik sebanyak 8%. Akhir sekali, kajian berangka tiga dimensi dilakukan untuk membandingkan data eksperimen untuk kedua-dua suhu dan pelepasan (NO_x dan CO) pada nisbah setara kritikal (ER = 0.7).

PERFORMANCE CHARACTERIZATION OF MICRO POROUS MEDIA BURNER FOR HEAT OR POWER GENERATION

ABSTRACT

The threat of fossil fuel depletion affects the nation's economy. Consequently, attempts are made to improve the use of fuels by developing highly efficient burners. With this intention, present work was focused to develop premixed butane based micro porous media burner. The burner was designed to undergo surface and submerged flames by varying equivalence ratio. Two types of reaction layer were tested; foam and ball type porous media (PM), while porcelain foam in preheat zone. Thickness of reaction and preheat layer was varied suitably to get optimum burner performance. Thus 90% thermal efficiency was noted by using 15 mm alumina foam along with 10 mm porcelain foam. Values of NO_x and CO at optimum equivalence ratio was less than 15 and 60 ppm respectively. Further, 4% improvement in the thermal efficiency was achieved by adding 80 μL of vegetable oil droplets over reaction layer. In addition, electric power of 2.018 W was generated from the surface flame using TE cells. These TE cells are integrated to a hybrid configuration, it includes circuit fan powered from solar panels. Moreover, height between reaction layer and TE cells was optimized (69 mm) using design of experiments to further increase electric power by 8%. Finally, three dimensional numerical study was performed to compare experimental data for both temperature and emissions (NO_x and CO) at a critical equivalence ratio (ER=0.7).

CHAPTER ONE

INTRODUCTION

1.1 General Introduction

The major direct impact to any nation across the world is due to the fast depletion of fossil fuel. Every possible attempts are made to save even a small bit of fossil fuels in some way or the other. One of the most popular device which consumes large amount of fossil fuels are burners, which are extensively used in domestic and industrial sectors. Nowadays, major international organizations such as WHO (World Health Organization) and IUAPPA (International Union of Air Pollution Prevention and Environmental Protection Associations) have made direct mandatory rules for both domestic and industrial sectors in controlling air pollution caused by fossil fuels. Thus, porous media burner (PMB) have gained popularity because of their outstanding performance in terms of technical and economic aspects, especially the burners with premixing and a two-layered structure (Mujeebu et al., 2009a).

A porous material can be defined as “a material with a specific size and number of pores, which are well connected to each other to form a solid shape”. Porous media (PM) have become popular choice because of their ability to generate better heat transfer between combustible and solid media, as well as the dispersion of the reactant in the reaction zone. Generally, once combustion in PMB gains better thermal efficiency, the by-products of emissions such as NO_x, shows less than 10 ppm (parts per million) (Mujeebu et al., 2011a). A literature survey from the past three decades indicates good quality and quantity of work has reported on various

aspects and applications of porous media combustion (PMC). However, various aspects of dual layer PMB have yet to be confirmed, especially when it comes to presence of preheat layer. Exhaustive reviews on PMB indicate a the good scenario on the development of innovative and efficient burners (Mujeebu et al., 2009a; Mujeebu et al., 2009b). Ismail et al. (2013) made a successful breakthrough experimental study with butane as a source fuel to revolutionize the conventional use of LPG for cogeneration applications with foam type of porous media (PM). Exclusive research reported from (Ismail et al., 2013; Ismail et al., 2016) on butane PM burners highlighted the importance of butane for reduction of emissions and stable surface temperatures at various ER, thereby performs better over LPG.

Literature on PMB identifies the popular methods used to increase thermal efficiency includes usage of a unique fuel mixtures, changing the thickness of the reaction/preheat layer, and replacing PM with new materials (Mujeebu et al., 2010).

Another possible method to improve burner characteristics is by using external additives/fuels over the reaction zone. Lapirattanakun and Charoensuk (2017) developed a novel PMB that works with vegetable oil (VO) along with steam injection. Their PMB achieved significant improvement in thermal efficiency. Thus, VO can be regarded as a stand-alone or a biofuel input to develop a cooking stove, a semi-industrial boiler, and a liquid PMB cogeneration applications (Mustafa, 2015). VO can also be an interesting alternative to consider as external additives/fuels for boosting conventional combustion systems. Another important concern by researchers was that the heat generated from the burner should not just be limited to domestic/industrial heat supply but also support cogeneration system. Therefore, many studies focused on cogeneration system with porous media burners utilize the heat from the exhaust/walls to convert it into other forms of energy. One of the

popular ways to generate electric power from heat energy is by considering Thermoelectric (TE) cells. It operates on the phenomenon of Seebeck effect which produces electric voltage when subjected to temperature gradient across two dissimilar metals (which are fused together). Consequently, power output from TE cell can be further increased provided the temperature difference across two surfaces of the cell are kept higher.

1.2 Problem Statement

The combustion of fossil fuels is an important aspect for both domestic and industrial sector to act as power source. Even though tremendous amount of experimental work has been carried out to improve combustion in burner, but still there is a need to improve burner thermal efficiency to much greater level since fuels are getting expensive day by day. Especially in a burner which can generate submerged flame, since submerged flame gives pure radiation and finds good number of applications in domestic and industrial sectors such as in bakery, cosmetic companies and textile industries. Apart from aiming to improve thermal efficiency, major concern is to focus on reduction of emission parameters like NO_x and CO. The emission generated during combustion mainly depend on physical and chemical mechanisms involved during combustion (Mohamad, 2005). Hence there is almost need for new burner with better thermal efficiency and low emissions.

Porous media burner (PMB) are able to generate two types of flame, namely surface and submerged flame. The flame that can be easily seen by the naked eye is called a surface flame, where in the actual movement of flame can be easily noticed. While, the flame that runs under the surface of reaction zone is known as a submerged flame. Submerged flame can directly heat the objects in a common

environment, not the air in between. Hence, heat transfer study with surface/submerged flame in a burner can be an interesting aspect of the study. Selection of PM inside burner is a challenging task. Three main factor play important role in building novel PMB includes type of PM to installed in reaction and preheat layer, porosity and ppcm (pores per centimetres). In addition, mechanism of stable combustion phenomenon depends on burner size, and type of incoming fuel mixture. Size of the PMB are decided based on the actual application of the burner, cost of the system, required flame type and available PM. Next, importance of fuel identification is a critical aspect, since commercially available fuels are obtained from fossil fuels. Gaseous fuels like methane, propane, butane and LPG finds their own advantages and limitations based on application of the burner.

Thermal efficiency can also be enhanced by the using suitable combustion enhancing liquids like vegetable oil, spraying nano particles and biofuel spray. These liquids release additional energy during combustion, thereby increases thermal efficiency. Involvement of external liquids can be utilized in different ways either over surface of the reaction zone or it can be injected between porous media. Considering vegetable oil to enhance efficiency is an interesting option, due to its availability. Since the triglycerides present in vegetable oil contains significant amount of oxygen, which enhances combustion (Mustafa, 2015).

Heat energy from the burner can also be utilized to convert in to electric power by using energy conversion cells. Since electric power is very much essential for electronic gadgets like; mobile phone and portable LED lamps. Generally, thermoelectric (TE) or thermophotovoltaic (TPV) are the potential candidate in conversion of heat energy in to electrical energy with respect to burners. Therefore, the need to generate both heat and electrical power generation by micro burner can

be considered as better approach of study. Hence, by focusing on low fuel consuming burner, emission perspectives, external additives to boost thermal efficiency and electric power generation all together shall give rise to new research and development in the area of burners.

1.3 Objectives of the study

The objectives of the study are listed below,

- I. To develop a dual layered micro porous media burner to undergo both surface and submerged flames at low fuel mixture.
- II. To obtain the performance of porous media burner experimentally by using foam and ball type of porous media with various thickness of reaction and preheat layers.
- III. To investigate the effect of vegetable oil droplets during porous media combustion at various equivalence ratios.
- IV. To measure the electric power using thermoelectric cells with the help of hybrid configuration.

1.4 Scope of the Study

The scope and limitation of the study are given below,

- I. The fabricated burner was designed only to undergo surface and submerged flame at low fuel rate, in order to save the fuel.
- II. Porous media used in the study was limited to the alumina foam and ball type; alumina and zirconia sphere with 10 mm size.

- III. Only butane as a gaseous fuel was used throughout the experimental trials with equivalence ratio from 1 to 0.4.
- IV. Vegetable oil was varied from of 20 to 80 μL in steps of 20 μL .
- V. Only thermoelectric cells where used to generate electric power.
- VI. Optimum height at which thermoelectric cells need to be located was determined using RSM optimization technique.
- VII. Three dimensional numerical analysis using ANSYS FLUENT with standard governing equation and global reaction mechanism was conducted in the study at only critical equivalence ratio only.

1.5 Thesis overview

This thesis consists of five chapters, with this first chapter highlights on general introduction about the work done. Chapter two highlights on research work carried out by previous researchers. It basically summarizes the research trends and findings with respect to the study of porous media combustion especially involving various types of burner used by other researchers for domestic and industrial applications. For better understanding a detailed discussion on types of flames i.e., surface and submerged flame was added. Importance of adding external liquids to enhance porous media combustion (PMC) was also focused. It is worth to be noted that the impact of external liquids shall enhance performance of burner, thereby generating high thermal efficiency.

Next, chapter three highlights main aspects of methodology adopted. It includes detailed explanation on how presented work was performed with justified