



# MODELLING OF COMBUSTION IN A SINGLE-BURNER BIOGAS FIRED COOKING STOVE



By  
University of Moratuwa, Sri Lanka  
Electronic Theses & Dissertations  
www.lib.mrt.ac.lk

**R.M.P.S. Bandara**

621.05  
620.95043

This thesis was submitted to the Department of Mechanical Engineering of the University of Moratuwa in partial fulfillment of the requirements for the Degree of Master of Engineering in Energy Technology

University of Moratuwa



85959

**Department of Mechanical Engineering**

**University of Moratuwa**

**Sri Lanka**

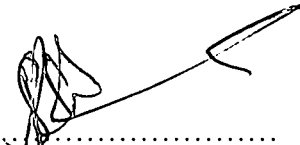
**February 2005**

85959

85959

## DECLARATION

“I certify that this thesis does not incorporate, without acknowledge, any material previously submitted for a degree or diploma in any university or higher educational institution in Sri Lanka or abroad and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text”.

  
.....  
Supervisor



University of Moratuwa, Sri Lanka  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

  
.....  
R.M.P.S. Bandara


85959

## ABSTRACT

A variety of stoves are used for household cooking in Sri Lanka. Fuel-wood, Liquefied Petroleum Gas (LPG), Electricity, Kerosene oil, Biogas etc. are the common cooking fuels used. Combustion process in a cooking stove is a complicated phenomenon. It is very difficult to predict the distributions of temperature, flow properties and combustion product concentrations of the cooking stove. It is emphasized that a detailed understanding of the combustion process taking place in a cooking stove is essential for the development of better stove designs. Computational modelling is an efficient tool that could be used successfully in describing the combustion in cooking stoves. Modelling of combustion in a cooking stove that uses a gaseous fuel is comparatively easier than that uses a solid fuel, mainly due to the complexity of the combustion process that the solid fuel undergoes. On this basis present work is involved in the modelling of combustion taking place in a biogas fired cooking stove using *SOFIE*, a Computational Fluid Dynamics (CFD) code extensively used for fire modelling. The combustion flow field of the stove has been modelled using the  $k-\epsilon$  turbulence model for turbulence and one-step reaction fast chemistry represents combustion chemistry. Simulations are conducted for the biogas cooking flame alone and also for the single-burner biogas fired stove with a square-shaped cooking pan. Temperature, density and combustion product concentration predictions have been made using simulations. The predicted temperatures are compared with the experimental measurements. The results generated could be used as a basis for further research in combustion in cooking stoves in order to develop better designs.

## ACKNOWLEDGEMENT

I am highly grateful to Dr. Rohitha Weerasinghe, my Supervisor, for the invaluable guidance, assistance and encouragement given to me throughout the course of this event that contributed immensely to the successful completion of the research study. I also wish to thank Dr. Rahula Attalage, Head, Department of Mechanical Engineering (former course coordinator of M.Eng. Programme), Dr. Thusitha Sugathapala, the Course Coordinator of the Master of Engineering Programme in Energy Technology and Dr. Kapila Perera, Senior Lecturer in Mechanical Engineering, for the vital advice and instructions given to me at crucial stages of the research.

Special regards should go to Mr. D. D. Weerakkody, the former Director General, Mr. Percy Gunawardane, the former Director in Curriculum Development and Mr. Hubert Kalugampitiya, Director/Human Resources Development of the National Institute of Technical Education of Sri Lanka, Ratmalana for granting me duty leave to follow the programme without any  obstructions and the encouragement given to me throughout. I also appreciate the contributions made by Mr. V R I Gunawardane, Mr. Yapa Karunaratne, Mr. Suraj Jayathilake and Mr. L. Ranathunga together with the academic and non-academic staff of NITESL.


I would also wish to thank Mr. Upali Wanigaratne for providing me with biogas for the experiments.

Finally, the support of my friends, Mr. Leslie Kumara, Mr. Himan Punchihewa, Mr. Suranga Karawita, Mr. Saliya Jayasekera, Mr. Avantha De Silva, Miss Udeshika Lakmali, Mr. Ajantha Egodawatte and Mr. Janath Priyankara at University of Moratuwa is very much appreciated.

# CONTENTS

<b>List of Tables</b>	<b>VIII</b>
<b>List of Figures</b>	<b>IX</b>
<b>List of Appendices</b>	<b>XI</b>
<b>Nomenclature</b>	<b>XII</b>
<b>1. Introduction</b>	<b>01</b>
1.1 Overview	01
1.2 Related Issues	02
1.2.1 Impact due to low Overall Stove Efficiency	02
1.2.2 Health Impacts of Combustion Emissions	03
1.3 Research Problem	04
1.4 Possible Solutions	05
1.5 Computational Fluid Dynamics (CFD) Software	07
1.6 Overview of thesis	08
<b>2. Cooking Technology in Sri Lanka</b>	<b>09</b>
2.1 Food Consumption Pattern in Sri Lanka	09
2.2 Cooking Stoves used in Sri Lanka	09
2.2.1 Traditional Cooking Stoves	09
2.2.2 Improved Traditional Cooking Stoves	10
2.2.3 Modern Cooking Stoves	11
2.3 Typical Characteristics of Cooking Fuels	12
2.4 Typical Characteristics of Cooking Stoves	13
2.5 Cooking Applications	13
2.5.1 Boiling	13
2.5.2 Frying	14
2.5.3 Baking	14
2.5.4 Grilling	14
2.5.5 Steaming	14
2.5.6 Pressure cooking	14

2.6	Distribution of Cooking Stoves in Sri Lanka	15
<b>3.</b>	<b>Governing Equations</b>	<b>17</b>
3.1	Introduction	17
3.2	Physical Models	19
3.2.1	Turbulence Model	19
3.2.2	Combustion Model	21
3.2.3	Heat Transfer Model	22
3.2.4	Discrete Transfer Radiation Model	22
3.2.5	Buoyancy Model	25
3.3	Generation of Computational Model	27
<b>4.</b>	<b>Solution Methodology</b>	<b>28</b>
4.1	Numerical Simulation Approach	28
4.2	Prototype	29
4.3	Computational Model	30
4.3.1	Simulation of Biogas Cooking Flame	30
4.3.2	Simulation of Stove with the Cooking Pan	31
4.4	Computer Simulation	33
4.4.1	Inputs	33
	4.4.1 (a) VRML1 files	33
	4.4.1 (b) Script files	33
4.4.2	Outputs	34
	4.4.2 (a) vtk files	34
	4.4.2 (b) Text files	34
4.5	Experimental Procedure	36
4.5.1	Flame Temperature Measurements	36
4.5.2	Cooking Pan Temperature Measurements	37
<b>5.</b>	<b>Simulation &amp; Experimental Results</b>	<b>38</b>
5.1	Simulation of Biogas Cooking Flame	38
5.1.1	Predicted Flame Temperature	38
5.1.2	Predicted Density	43
5.1.3	Predicted CO <sub>2</sub> Mole Fraction	44

5.1.4	Predicted H <sub>2</sub> O Mole Fraction	45
5.1.5	Predicted O <sub>2</sub> Mole Fraction	46
5.1.6	Summary of Predictions	47
5.2	Simulation of Biogas Flame with Cooking Pan	48
5.2.1	Predicted Cooking Pan Temperature	48
5.2.2	Predicted Density Distribution	51
5.2.3	Predicted CO <sub>2</sub> Mole Fraction	52
5.2.4	Predicted H <sub>2</sub> O Mole Fraction	52
5.2.5	Predicted O <sub>2</sub> Mole Fraction	53
5.2.6	Summary of Predictions	53
<b>6.</b>	<b>Conclusions &amp; Discussion</b>	<b>54</b>
6.1	Issues in Computational Modelling	54
6.2	Issues in Experimentation	56
6.3	Areas for further work	58
<b>Bibliography</b>	 University of Moratuwa, Sri Lanka. Electronic Theses & Dissertations <a href="http://www.lib.mrt.ac.lk">www.lib.mrt.ac.lk</a>	<b>60</b>
<b>Appendices</b>		<b>64</b>

## LIST OF TABLES

1	Average quantity of monthly usage of energy sources in cooking	01
2	Types and efficiencies of cooking stoves tested	02
3	Emissions generated from fuel-wood fired cooking stoves in Sri Lanka	04
4	Characteristics of cooking fuels	12
5	Efficiencies and emissions of cooking stoves	13
6	Percentage of cooking stoves used by rural households	15
7	Stove distribution among urban & rural populations of Sri Lanka	15
8	Boundary/Initial conditions for the simulation on biogas flame	31
9	Boundary/Initial conditions for the simulation on biogas flame with the cooking pan	33
10	Temperature predictions for biogas flame	39
11	Experimental temperature measurements for biogas flame	39
12	Conditions at point of maximum combustion intensity	47
13	Predicted cooking pan radial temperature data	49
14	Experimental cooking pan radial temperature measurements	49
15	Conditions at point of maximum combustion intensity	53
16	Temperature measurement uncertainty data for the flame centreline	73
17	Radial temperature measurement uncertainty data for the cooking pan	74



## LIST OF FIGURES

1	Predicted temperature profile of a biogas flame	06
2	Traditional cooking stoves in Sri Lanka	10
3	Improved traditional cooking stoves developed during 1983-1987	11
4	Modern cooking stoves	11
5	Conventional discretization of the solid angle hemisphere	23
6	Generation of computational model from the governing equations	27
7	Simple biogas stove & cooking pan	29
8	Cooking application	29
9	Computational fluid dynamics model	30
10	Solution domain for the simulation of biogas flame	30
11	Computational fluid dynamics model	31
12	Solution domain for the stove simulation	32
13	Computer simulation flow chart	35
14	Experimental arrangement of biogas flame temperature measurements	36
15	Experimental arrangement of cooking pan temperature measurements	37
16	Temperature distribution predictions of biogas flame	38
17	Predicted temperature vs. centreline height of biogas flame	38
18	Experimental horizontal temperature profiles of biogas flame	40
19	Predicted and experimental centreline temperature profiles of biogas flame	41
20	Density distribution predictions of biogas flame	43
21	Predicted flame density vs. centreline height of biogas flame	43
22	CO <sub>2</sub> mole fraction predictions of biogas flame	44
23	Predicted CO <sub>2</sub> mole fraction vs. centreline height of biogas flame	44
24	H <sub>2</sub> O mole fraction predictions of biogas flame	45
25	Predicted H <sub>2</sub> O mole fraction vs. centreline height of biogas flame	45
26	O <sub>2</sub> mole fraction predictions of biogas flame	46
27	Predicted O <sub>2</sub> mole fraction vs. centreline height of biogas flame	46
28	Predicted temperature distribution on cooking pan	48
29	Predicted cooking pan radial temperature profile	48
30	Predicted & experimental radial temperature profiles of cooking pan	50

31	Predicted density distribution of cooking stove	51
32	Predicted CO <sub>2</sub> mole fraction distribution of cooking stove	52
33	Predicted H <sub>2</sub> O mole fraction distribution of cooking stove	52
34	Predicted O <sub>2</sub> mole fraction distribution of cooking stove	53
35	Biogas flame simulation convergence details	70
36	Biogas fired cooking stove simulation convergence details	71
37	Uncertainty of biogas centreline flame temperature	73
38	Uncertainty of cooking pan radial surface temperature	75



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## LIST OF APPENDICES

A. Biogas flame simulation script file – <i>flame.com</i>	64
B. Biogas flame and cooking pan simulation script file – <i>pan.com</i>	67
C. Convergence details of the biogas flame simulation	70
D. Convergence details of the simulation of biogas flame with the cooking pan	71
E. Temperature measurement error/uncertainty analysis	72



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## NOMENCLATURE

$D_f$	Fin diameter (m)
$g$	Acceleration due to gravity ( $\text{ms}^{-2}$ )
$h$	Heat transfer coefficient ( $\text{Wm}^{-2}\text{K}^{-1}$ )
$k$	Turbulent kinetic energy ( $\text{m}^2\text{s}^{-2}$ )
$k_f$	Thermal conductivity of fin material ( $\text{Wm}^{-1}\text{K}^{-1}$ )
$L$	Length of fin (m)
$m_{fu}$	Time averaged mass fraction of fuel
$m_{ox}$	Time averaged mass fraction of oxidant
$p$	Thermodynamic pressure ( $\text{Nm}^{-2}$ )
$q_f$	Rate of conduction heat loss from a long fin (W)
$q_w$	Wall heat flux ( $\text{Wm}^{-2}$ )
$T_c$	Fin-end temperature (K)
$T_f$	Flame temperature (K)
$T_o$	Base temperature of fin (K)
$T_p$	Temperature at near wall point (K)
$T_s$	Sensor temperature (K)
$T_w$	Wall temperature (K)
$T_\alpha$	Ambient air temperature (K)
$t$	Time (s)
$U$	Velocity ( $\text{ms}^{-1}$ )
$Y_\alpha$	Mass fraction of species $\alpha$



## Greek Symbols

$\varepsilon$	Dissipation of the turbulent kinetic energy ( $\text{m}^2\text{s}^{-3}$ )
$\varepsilon_{th}$	emissivity of the thermocouple junction surface
$\theta$	Polar angle (rad.)
$\kappa$	Von Karman constant
$\mu$	Mixture molecular viscosity ( $\text{Nsm}^{-2}$ )
$\mu_t$	Turbulent eddy viscosity ( $\text{Nsm}^{-2}$ )
$\nu$	Kinematic viscosity ( $\text{m}^2\text{s}^{-1}$ )
$\rho$	Density of the mixture ( $\text{kgm}^{-3}$ )
$\sigma$	Stefan-Boltzmann constant ( $\text{Wm}^{-2}\text{K}^{-4}$ )
$\sigma_t$	Turbulent Prandtl/Schmidt number
$\tau$	Characteristic turbulent time scale (s)
$\tau_\nu$	Spectral transmissivity
$\tau_w$	Wall shear stress ( $\text{Nm}^{-2}$ )
$\Phi$	Azimuthal angle (rad.)