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

By

R.M.P.S. Bandara

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

Department of Mechanical Engineering
University of Moratuwa
Sri Lanka
February 2005
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

R.M.P.S. Bandara
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-ε 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

List of Tables VIII
List of Figures IX
List of Appendices XI
Nomenclature XII

1. Introduction 01
   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

2. Cooking Technology in Sri Lanka 09
   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
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Average quantity of monthly usage of energy sources in cooking</td>
<td>01</td>
</tr>
<tr>
<td>2</td>
<td>Types and efficiencies of cooking stoves tested</td>
<td>02</td>
</tr>
<tr>
<td>3</td>
<td>Emissions generated from fuel-wood fired cooking stoves in Sri Lanka</td>
<td>04</td>
</tr>
<tr>
<td>4</td>
<td>Characteristics of cooking fuels</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Efficiencies and emissions of cooking stoves</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Percentage of cooking stoves used by rural households</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>Stove distribution among urban &amp; rural populations of Sri Lanka</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Boundary/Initial conditions for the simulation on biogas flame</td>
<td>31</td>
</tr>
<tr>
<td>9</td>
<td>Boundary/Initial conditions for the simulation on biogas flame with the cooking pan</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>Temperature predictions for biogas flame</td>
<td>39</td>
</tr>
<tr>
<td>11</td>
<td>Experimental temperature measurements for biogas flame</td>
<td>39</td>
</tr>
<tr>
<td>12</td>
<td>Conditions at point of maximum combustion intensity</td>
<td>47</td>
</tr>
<tr>
<td>13</td>
<td>Predicted cooking pan radial temperature data</td>
<td>49</td>
</tr>
<tr>
<td>14</td>
<td>Experimental cooking pan radial temperature measurements</td>
<td>49</td>
</tr>
<tr>
<td>15</td>
<td>Conditions at point of maximum combustion intensity</td>
<td>53</td>
</tr>
<tr>
<td>16</td>
<td>Temperature measurement uncertainty data for the flame centreline</td>
<td>73</td>
</tr>
<tr>
<td>17</td>
<td>Radial temperature measurement uncertainty data for the cooking pan</td>
<td>74</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>Predicted temperature profile of a biogas flame</td>
<td>06</td>
</tr>
<tr>
<td>2</td>
<td>Traditional cooking stoves in Sri Lanka</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Improved traditional cooking stoves developed during 1983-1987</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>Modern cooking stoves</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>Conventional discretization of the solid angle hemisphere</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>Generation of computational model from the governing equations</td>
<td>27</td>
</tr>
<tr>
<td>7</td>
<td>Simple biogas stove &amp; cooking pan</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>Cooking application</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>Computational fluid dynamics model</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>Solution domain for the simulation of biogas flame</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>Computational fluid dynamics model</td>
<td>31</td>
</tr>
<tr>
<td>12</td>
<td>Solution domain for the stove simulation</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>Computer simulation flow chart</td>
<td>35</td>
</tr>
<tr>
<td>14</td>
<td>Experimental arrangement of biogas flame temperature measurements</td>
<td>36</td>
</tr>
<tr>
<td>15</td>
<td>Experimental arrangement of cooking pan temperature measurements</td>
<td>37</td>
</tr>
<tr>
<td>16</td>
<td>Temperature distribution predictions of biogas flame</td>
<td>38</td>
</tr>
<tr>
<td>17</td>
<td>Predicted temperature vs. centreline height of biogas flame</td>
<td>38</td>
</tr>
<tr>
<td>18</td>
<td>Experimental horizontal temperature profiles of biogas flame</td>
<td>40</td>
</tr>
<tr>
<td>19</td>
<td>Predicted and experimental centreline temperature profiles of biogas flame</td>
<td>41</td>
</tr>
<tr>
<td>20</td>
<td>Density distribution predictions of biogas flame</td>
<td>43</td>
</tr>
<tr>
<td>21</td>
<td>Predicted flame density vs. centreline height of biogas flame</td>
<td>43</td>
</tr>
<tr>
<td>22</td>
<td>CO₂ mole fraction predictions of biogas flame</td>
<td>44</td>
</tr>
<tr>
<td>23</td>
<td>Predicted CO₂ mole fraction vs. centreline height of biogas flame</td>
<td>44</td>
</tr>
<tr>
<td>24</td>
<td>H₂O mole fraction predictions of biogas flame</td>
<td>45</td>
</tr>
<tr>
<td>25</td>
<td>Predicted H₂O mole fraction vs. centreline height of biogas flame</td>
<td>45</td>
</tr>
<tr>
<td>26</td>
<td>O₂ mole fraction predictions of biogas flame</td>
<td>46</td>
</tr>
<tr>
<td>27</td>
<td>Predicted O₂ mole fraction vs. centreline height of biogas flame</td>
<td>46</td>
</tr>
<tr>
<td>28</td>
<td>Predicted temperature distribution on cooking pan</td>
<td>48</td>
</tr>
<tr>
<td>29</td>
<td>Predicted cooking pan radial temperature profile</td>
<td>48</td>
</tr>
<tr>
<td>30</td>
<td>Predicted &amp; experimental radial temperature profiles of cooking pan</td>
<td>50</td>
</tr>
<tr>
<td>Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>31</td>
<td>Predicted density distribution of cooking stove</td>
<td>51</td>
</tr>
<tr>
<td>32</td>
<td>Predicted CO₂ mole fraction distribution of cooking stove</td>
<td>52</td>
</tr>
<tr>
<td>33</td>
<td>Predicted H₂O mole fraction distribution of cooking stove</td>
<td>52</td>
</tr>
<tr>
<td>34</td>
<td>Predicted O₂ mole fraction distribution of cooking stove</td>
<td>53</td>
</tr>
<tr>
<td>35</td>
<td>Biogas flame simulation convergence details</td>
<td>70</td>
</tr>
<tr>
<td>36</td>
<td>Biogas fired cooking stove simulation convergence details</td>
<td>71</td>
</tr>
<tr>
<td>37</td>
<td>Uncertainty of biogas centreline flame temperature</td>
<td>73</td>
</tr>
<tr>
<td>38</td>
<td>Uncertainty of cooking pan radial surface temperature</td>
<td>75</td>
</tr>
</tbody>
</table>
LIST OF APPENDICES

A. Biogas flame simulation script file – flame.com 64
B. Biogas flame and cooking pan simulation script file – pan.com 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
NOMENCLATURE

\( D_f \)  Fin diameter (m)
\( g \)  Acceleration due to gravity (ms\(^{-2}\))
\( h \)  Heat transfer coefficient (Wm\(^{-2}\)K\(^{-1}\))
\( k \)  Turbulent kinetic energy (m\(^2\)s\(^{-2}\))
\( k_f \)  Thermal conductivity of fin material (Wm\(^{-1}\)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 (Nm\(^{-2}\))
\( q_f \)  Rate of conduction heat loss from a long fin (W)
\( q_w \)  Wall heat flux (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)
\( T_a \)  Ambient air temperature (K)
\( t \)  Time (s)
\( U \)  Velocity (ms\(^{-1}\))
\( Y_a \)  Mass fraction of species \( a \)

Greek Symbols

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