Investigations into Wood Combustion in Biomass Cookstoves

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Abstract

Three billion people use cookstoves across the globe for cooking, cleaning and heating. These cookstoves use biomass, which although renewable, produces harmful emissions when burned. The emissions produced include those from complete combustion; nitric oxides (NO\textsubscript{x}) and carbon dioxide (CO\textsubscript{2}) as well as those from incomplete combustion; carbon monoxide (CO), volatile organic compounds (VOC) and fine particles (PM\textsubscript{2.5–10}). It is the exposure to such emissions which cause between 2 and 4 million deaths every year. These deaths can be prevented by using improved cookstoves that reduce harmful emissions and increase fuel efficiency. In addition to health issues, there are many environmental issues such as deforestation and anthropogenic climate change which result from the use of these cookstoves. However, the application of scientific knowledge to support the development of improved cookstoves has previously been limited. The aim of the current project is to experimentally investigate and thus further the understanding of wood combustion in a typical cookstove.

Experiments were conducted in a furnace analogous to a Top-Lit, Up-Draft (TLUD) cookstove. The furnace and TLUD stoves are lit from above and use induced primary air to pyrolyse the fuel.

The suitability of the research furnace as an analogy to a real world biomass cookstove was a main aim to be investigated. This involved assessing the emissions produced by the combustion of wood as a fuel through systematic experimentation. This systematic experimentation included varying the primary and secondary air ratios to understand the optimum level of emissions and efficiency. A simulation of the furnace in the real world was then carried out by using the natural draught alone, which enabled a comparison and showed whether the research furnace was a suitable analogy to the real world biomass cookstove.

Measurements taken during the experiments include the emissions produced, the outer temperature of the furnace chamber and the temperature of the water for a water boiling test. A Testo\textsuperscript{TM} gas analyser was used to record the emissions, an infrared thermometer operated manually was used to record the outer temperature of the furnace chamber and a K-type thermocouple was used to record the water temperature.

Varying the secondary air and primary air flow rate showed very consistent results. Although consistent results were gained, results indicate that the higher the secondary air flow rate, the higher the O\textsubscript{2} emissions, lower CO and CO\textsubscript{2} emissions and a slightly prolonged time for 2 litres of water to boil. However, allowing just the natural draught to combust the fuel, the emissions and water boiling efficiency did not match those produced through the fan-forced approach. This concludes that the research furnace is not a suitable analogy to the real world biomass cookstove in its present state but would be
suitable for larger industry based combustion needs in the third world. This therefore indicates that future work aiming to gain a further understanding behind wood burning in cookstoves is required.
Acknowledgements

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- The School of Mechanical Engineering for use of equipment
Acronyms

AFR  African Region
ALRI  Acute Lower Respiratory Infections
AMR  Region of the Americas
BDS  Berkeley-Darfur Stove
CCT  Controlled Cooking Test
COPD  Chronic Obstructive Pulmonary Disease
EMR  Eastern-Mediterranean Region
EUR  European Region
EWP  The Experimental Work Plan
FT  Flue Temperature
GHG  Greenhouse Gases
KPT  Kitchen Performance Test
LCA  Life-Cycle Assessment
LDC  Least Developed Countries
LEDC  Less Economically Developed Countries
OCT  Outer Cylinder Temperature
PA  Primary Air
PDSP  Project Definition Statement and Plan
PHAIR  Pre-heated air improved rocket
PM  Preventive Measures
PM$_{2.5-10}$ Particulate Matter
PPE  Personal Protective Equipment
PWM  Pulse Width Modulation
SA  Secondary Air
SEAR  South-East Asian Region
TC  Thermocouple
TLUD  Top-Lit Up Draft
VOC  Volatile Organic Compounds
WB  Week Beginning
WBT  Water Boiling Test
WE  Week Ending
WHO  World Health Organization
WPR  Western Pacific Region
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Chapter 1

Introduction

1.1 Background

Three billion people around the world use cookstoves as their primary method of cooking, cleaning and heating (Cordes, 2011). The majority of these users live in rural areas in less economically developed countries (LEDC) across much of Africa and Asia where people generally live below the poverty threshold (WHO, 2007). For a large proportion of these people, they are limited with their money or facilities which hinders their access to clean cookstoves. They have traditionally collected biomass from local resources and burned it in small open fires or cookstoves. It is for both of these reasons that they still cook with biomass cookstoves.

Biomass is a renewable resource as it can be continuously produced and re-produced. However, unlike other renewable energy sources such as wind and solar power, biomass combustion does release emissions into the atmosphere, similar, but on a smaller scale, to the burning of fossil fuels (Loo and Koppejan, 2002). It is the small scale short term effects on the human population which is of major concern.

There are between 2 and 4 million premature deaths every year from the users of biomass cookstoves (GACC, 2013). This is due to the amount of harmful, toxic emissions that are produced. Many others will have life-long health issues, namely respiratory, burns and back problems. These users may even realise this but are unable to do anything about it. Women and children are most likely to be at the greatest risk, as in these developing countries the cooking and fuel collection still remains largely a woman’s responsibility (GACC, 2013). Young children are often carried around on their mothers back and hence are also at a greater risk.

It is therefore a priority to reduce these numbers of deaths by using the scientific knowledge and technology available to developed countries. By using a research furnace designed and built specifically for this, systematic tests can be carried out to identify the aspects of the top-lit up draft cookstove which allow fewer harmful emissions to be released and to be fuel efficient.
1.2 Objectives, Aims and Scope

This project is based on investigating the process of wood combustion in biomass cookstoves. A research furnace analogous to a Top-Lit, Up-Draft (TLUD) cookstove is the sole focus of the project. A main objective of the project is to assess the suitability of the research furnace as an analogy to the real world biomass cookstove. To do this, systematic experimentation will be conducted whereby the primary air flow rate and the secondary air flow rate will be varied. A simulation of the real world cookstoves will then be conducted by allowing the furnace to run using just the natural draught. The aims of this project will be to measure the emissions for each experiment, along with the temperatures of the furnace walls and exit gases to further understand how the fuel is burning. A pot of water will be placed above the furnace and the temperature continuously recorded to understand the efficiency. This will then enable a comparison between the fan-forced and natural draught combustion, thus indicating if the research furnace is a suitable analogy. The scope of this project will be to measure the level of oxygen ($O_2$), carbon dioxide ($CO_2$) and carbon monoxide (CO). Further emissions such as nitric oxides ($NO_x$), hydrogen ($H_2$) and sulphur oxides ($SO_x$) could also be measured but are beyond the scope of this project.

1.3 Document Structure

This Final Report provides a detailed literature review which highlights the importance of each aspect of biomass consumption, including the harmful emissions produced and the issues which result from this combustion. An Equipment and Techniques section explains the key equipment which was used throughout the project and the different techniques used to gain the appropriate results. The research furnace is explained in detail in this section along with the Testo gas analyser and their use in the experimentation. The testing procedures are explained along with the setup used. A Testing section gives rise to the results achieved through the systematic experimentation and an analysis is given along with a discussion. An Outcomes and Future Work section summarises the key findings and suggests improvements for this project and where the results could lead. The management of the project is then discussed before a conclusion summaries the project in its entirety.
Chapter 2

Literature Review

2.1 Fuels

Fuels can be classified as substances that liberate heat when reacted chemically with an oxidiser (McAllister et al., 2011). This is the basis of combustion. The oxidiser used is usually air as it is free and readily available almost everywhere on earth (McAllister et al., 2011). Oil, natural gas, coal and other non-renewable fossil sources dominate the current world energy supply and consumption (IEA, 2013) while the combustion of biomass provides a potentially renewable alternative (McAllister et al., 2011). However, due to the dominance of fossil fuel combustion, the renewable combustion of biomass fuels has limited scientific analysis.

Hall and Moss (1983) describe how biomass can be referred to as the energy from organic products produced through photosynthesis; ranging from waste products from cattle dung to residues from agricultural processes and from water plants and algae to trees and other crops which contain sugar, starch and oil. Depending on the definition of a renewable fuel/resource, biomass can often be considered to be CO$_2$ neutral with respect to the greenhouse gas balance (Loo and Koppejan, 2002). This is subjective as it doesn’t take into account the use of fossil fuels in harvesting, transportation and other electricity use of biomass fuels which a life-cycle assessment (LCA) would account for (Loo and Koppejan, 2002). This project will only focus on one type of fuel and as a LCA will not be carried out, the fuel will be referred to as renewable.

Vegetable oil, biodiesel, bioalcohols, biogas, solid biofuels and syngas are all different types of biofuel derived from biomass (McAllister et al., 2011). The most common types of biomass fuel are wood (both hard and soft), dung and crop residues due to their availability. This project will focus on wood biomass due to its ease of access, availability and ease of use.

Loo and Koppejan (2002) explain how drying and pyrolysis/gasification are the first stages of a solid fuel biomass combustion process prior to the oxidation. The drying process involves the removal of moisture in the material by evaporation. This is an important process in solid fuel combustion. As it would require a large amount of energy to evaporate the moisture and heat the water vapour, the combustion temperatures would decrease (Loo and Koppejan, 2002). For this reason it is known that the moisture content of the wood should not exceed 60% (Loo and Koppejan, 2002). Using this knowledge the fuel for
this project was to be dried prior to testing as is shown in Section 3.1. The pyrolysis and gasification stages are similar as they are both the devolatilisation process however pyrolysis is in the absence of an externally supplied oxidising agent whilst gasification is in the presence of the externally supplied oxidising agent (Loo and Koppejan, 2002). The final stage is the complete oxidation of the fuel which is known as the combustion stage.

2.2 Biomass Consumption

Three billion people use cookstoves or open fires for cooking, boiling water and heating homes (Cordes, 2011). This is approximately half of the world’s population who are exposed daily to the toxic emissions produced from these inefficient cookstoves, and as a result there are 2-4 million premature deaths per year (GACC, 2013). These deaths can be prevented with access to improved cooking systems, however the majority of these people live below the poverty threshold and therefore cannot afford the technology of those in the developed world. As a result of this there is a lack of scientific knowledge applied to the developing world. By simulating the cookstove environment, systematic studies of combustion can be carried out. This will lead to solutions which can be developed and implemented back into the developing world and will consequently save millions of people’s lives.

Biomass fuels make up 14% of today’s worldwide primary energy supply (Parikka, 2004), which is equivalent to 1000 million tons of oil per year (Hall and Moss, 1983). Approximately 25% of this usage is with industrialised countries while 75% is used in developing countries (Parikka, 2004). In developed countries this can be as low as 1-3%, but in the developing countries biomass is relied on for 43% of their primary energy source (Koziriski and Saade, 1998).

2.2.1 Location of Consumption

Figure 2.1 shows the usage of solid fuels for domestic use and indicates that Central Africa and South East Asia are the highest users, this is mainly due to the dense population and percentage of people living below the poverty threshold.

The globe can be divided up into six regions; the African Region (AFR), Region of the Americas (AMR), Eastern-Mediterranean Region (EMR), European Region (EUR), South-East Asian Region (SEAR) and Western Pacific Region (WPR). Within these regions, WHO (2000) gives data for acute lower respiratory infections (ALRI) in children under five and chronic obstructive pulmonary disease (COPD) in adults due to indoor air pollution. Table 2.1 summarises these figures.

African Region (AFR)

In the African region, more than half a billion people use solid fuels for cooking, heating and cleaning indoors (WHO, 2000). This is equivalent to 78% of the population in 2000 suggesting that only 22% of all those living in the African region have access to clean and efficient cooking facilities. It is for these reasons that over one third of all child deaths
2.2. BIOMASS CONSUMPTION

Figure 2.1: Map indicating use of solid fuel across the globe. Green shows usage less than 8.5% of the population whilst the red shows usage greater than 85% of the population (WHO, 2007)

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of users</th>
<th>% of population</th>
<th>COPD deaths</th>
<th>ALRI deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFR</td>
<td>500 million</td>
<td>78%</td>
<td>41,000</td>
<td>350,000</td>
</tr>
<tr>
<td>AMR</td>
<td>170 million</td>
<td>20%</td>
<td>11,000</td>
<td>15,000</td>
</tr>
<tr>
<td>EMR</td>
<td>200 million</td>
<td>42%</td>
<td>22,000</td>
<td>95,000</td>
</tr>
<tr>
<td>EUR</td>
<td>160 million</td>
<td>19%</td>
<td>10,000</td>
<td>15,000</td>
</tr>
<tr>
<td>SEAR</td>
<td>1.2 billion</td>
<td>78%</td>
<td>185,000</td>
<td>374,000</td>
</tr>
<tr>
<td>WPR</td>
<td>1.2 billion</td>
<td>71%</td>
<td>426,000</td>
<td>62,000</td>
</tr>
</tbody>
</table>

Table 2.1: Location of biomass consumption and related illnesses (WHO, 2000)
from indoor air pollution are in this region which equates to 350,000 deaths due to ALRI. COPD also accounts for 41,000 deaths leading to a total of nearly 400,000 deaths per year (WHO, 2000).

**Region of the Americas (AMR)** A large reduction in deaths occurs on the American supercontinent (WHO, 2000). Only 170 million people use solid fuel, namely wood and dung, in this region. This is only 20% of the region and as a result there are only 11,000 COPD deaths and 15,000 ALRI deaths per year (WHO, 2000). This region covers North America, Latin American and the Caribbean.

**Eastern-Mediterranean Region (EMR)** The EMR covers much of the Middle-East and includes countries in northern Africa. From these countries, 42% (200 million) of the population use solid fuels to cook with (WHO, 2000). This resulted in 118,000 deaths, of which 22,000 were from COPD and 95,000 from ALRI. The majority of solid fuel use in this region lies within the poorest countries while the oil-rich Gulf states tend to use gas and electricity for cooking (WHO, 2000).

**European Region (EUR)** 160 million in the European region rely on solid fuels to cook. The areas which this encompasses include all of Europe and parts of northern and central Asia. It is these newly independent states of Central Asia which are the predominant users of these solid fuels (WHO, 2000). Within the 19% of this region’s population, 21,000 deaths occurs annually from the combustion of these solid fuels.

**South-East Asian Region (SEAR)** 1.2 billion people in this region cook, wash and heat their homes with solid combustibles (WHO, 2000). This is 78% who cannot afford or do not have the technology to use gas or electricity. Of these 1.2 billion, 559,000 people die every year from indoor air pollution, of which 374,000 deaths are children under the age of five and 185,000 are adults (WHO, 2000).

**Western Pacific Region (WPR)** Another 1.2 billion in the WPR use these solid fuels indoors (WHO, 2000). This is 71% of the region’s population who do not have access to clean energy sources. 426,000 deaths are attributed to indoor air pollution from COPD along with 62,000 ALRI deaths (WHO, 2000). China lies in this region and here, only 20% of the population use other sources other than solid combustibles while in rural China, only 16% use gas and electricity.

It is these figures which show the extent to which these harmful emissions has on society. Within each region, there are also many different cooking styles and needs. This suggests that there is a need for tailored cooking stoves, of which the research furnace has the potential to achieve. In developing countries, indoor air pollution accounts for 3.7% and 1.9% of the overall disease burden for high and low-mortality rate countries respectively (WHO, 2000). In stark contrast, in industrialised countries this figure is negligible where tobacco, high blood pressure and alcohol consumption dominate (WHO, 2000).


2.3 Emissions

The process of biomass combustion can be divided into two categories; complete combustion and incomplete combustion. Complete combustion of biomass will produce nitric oxides (NO\textsubscript{x}), carbon dioxide (CO\textsubscript{2}) and water (H\textsubscript{2}O) (Nussbaumer, 2003). Ash and salts will also be produced and potentially sulphur oxides (SO\textsubscript{x}), hydrogen chloride (HCl) and heavy metals depending on the type of fuel (Loo and Koppejan, 2002). Incomplete combustion is caused by the inadequate mixing of fuel and oxygen, low temperatures or short residency times (Higgins et al., 2011). Carbon monoxide (CO), volatile organic compounds (VOC) and fine particles (PM\textsubscript{2.5-10}) are all products of incomplete combustion in addition to those formed through complete combustion (Loo and Koppejan, 2002). It is these emissions from incomplete combustion which are of major concern both to the human population and the environment and will be discussed in Section 2.5. Table 2.2 shows the pollutants produced during combustion.

Table 2.2: Pollutants of Combustion (Loo and Koppejan, 2002)

<table>
<thead>
<tr>
<th>Combustion Type</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete Combustion</td>
<td>CO\textsubscript{2}, NO\textsubscript{x} (NO and NO\textsubscript{2}), N\textsubscript{2}O, SO\textsubscript{x}, HCl, ash particles (KCl, etc.) and heavy metals (Cu, Pb, Zn, Cd, Hg etc.)</td>
</tr>
<tr>
<td>Incomplete Combustion</td>
<td>CO, C\textsubscript{x}H\textsubscript{y}, CH\textsubscript{4}, PAH, soot, char, tar, PCDD/F, NH\textsubscript{3}, O\textsubscript{3}</td>
</tr>
</tbody>
</table>

The combustion of biomass is a complex process which varies depending on fuel type and combustion environment. It is therefore an aspect which needs to be analysed through controlled, systematic experimentation where important aspects of the stove can be adjusted in addition to the fuel type and amount.

2.4 Standards

The World Health Organisation (WHO) gives guidelines on the acceptable levels of indoor air pollution. These guidelines are for the most dangerous emissions which over-exposure to can result in respiratory infection, diseases and death. Table 2.3 shows these guidelines.

Particles with a diameter of 10 microns or less (PM\textsubscript{10}) or with a diameter of 2.5 microns or less (PM\textsubscript{2.5}) are able to cause respiratory illnesses due to their ability to penetrate deep into the lungs (WHO, 2000). The smallest particles (PM\textsubscript{2.5}) are known to cause the greatest health issues as they can travel deeper into the lungs and are comprised of more toxic, cancer causing compounds (EPA, 2014). WHO (2000) also shows that the typical 24h mean levels for PM\textsubscript{10} for homes which use biomass fuels indoors is around 1000\textmu g/m\textsuperscript{3}. This shows the scale of pollution, as the acceptable level is only 50\textmu g/m\textsuperscript{3}. It is therefore necessary to reduce this value by focusing on the primary emission reduction methods.
CHAPTER 2. LITERATURE REVIEW

Table 2.3: WHO air quality guidelines (WHO, 2010b)

<table>
<thead>
<tr>
<th>Emission Type</th>
<th>Acceptable Exposure Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$</td>
<td>10µg/m$^3$ (annual mean)</td>
</tr>
<tr>
<td></td>
<td>25µg/m$^3$ (24h mean)</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>20µg/m$^3$ (annual mean)</td>
</tr>
<tr>
<td></td>
<td>50µg/m$^3$ (24h mean)</td>
</tr>
<tr>
<td>Ozone</td>
<td>100µg/m$^3$ (8h mean)</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>40µg/m$^3$ (annual mean)</td>
</tr>
<tr>
<td></td>
<td>200µg/m$^3$ (1h mean)</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>20µg/m$^3$ (24h mean)</td>
</tr>
<tr>
<td></td>
<td>500µg/m$^3$ (10min mean)</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>60mg/m$^3$ (30 min mean)</td>
</tr>
<tr>
<td></td>
<td>30mg/m$^3$ (1h mean)</td>
</tr>
<tr>
<td></td>
<td>10mg/m$^3$ (8h mean)</td>
</tr>
</tbody>
</table>

2.5 Issues

2.5.1 Social Issues

Data from WHO (2010a) shows that more men, women and children die every day from diseases that could be entirely prevented by using clean cookstoves than die from Malaria and Tuberculosis combined. The GACC (2013) states that exposure to cookstove smoke is the fifth worst risk factor for disease in developing countries. Women and children are likely to be at the greatest risk, as in these developing countries cooking and fuel collection remains largely a woman’s responsibility (GACC, 2013). But it is not only the substantial amount of deaths that are the issues resulting from non-clean cookstoves. Chronic lung disease and heart disease are just a few of the health issues, whilst many will suffer burns, potentially life threatening, and even disfigurement (Akbar et al., 2011), many of which are preventable with efficient cookstoves.

As can be seen, the emissions from this incomplete combustion are extremely dangerous, and hence the type and amount of these emissions will be tested during each experiment. By increasing the level of complete combustion carried out by the stoves, many respiratory illnesses and deaths can ultimately be prevented.

2.5.2 Environmental Issues

The combustion of biomass fuels has an affect on the local, regional and global environment (Loo and Koppejan, 2002). Loo and Koppejan (2002) continue on to explain that the local environment is mainly just affected by particle emissions from incomplete combustion, the regional environment is affected by acid precipitation caused by NO$_x$ and SO$_x$ and the global environment is affected by direct or indirect GHG and ozone depletion. The effect of anthropometric climate change is evident. During the 20th century the global surface temperature rose by 0.8°C and early predictions show that it is projected to increase by 1.4-5.8°C throughout the 21st century (Dhillon and von Wuehlisch, 2013).
Although the burning of biomass fuels is only a small cause of these issues, it is one of the few areas which the human population can actually have an impact on and change. This is therefore a key motivation for this project.

The emission of NO$_x$ and SO$_x$ from biomass combustion is low in comparison with the combustion of fossil fuels (Loo and Koppejan, 2002). The NO$_x$ produced from biomass combustion mainly originates from the nitrogen in the fuel while fossil fuel combustion also includes a component of nitrogen from the air (Loo and Koppejan, 2002). Primary emission reduction measures, which avoid the creation of the harmful gas, can significantly reduce the NO$_x$ level and occasionally the SO$_x$ level. Secondary emission reduction measures, which remove the harmful gases from escaping into the environment, can easily remove both NO$_x$ and SO$_x$.

Small-scale applications of biomass combustion such as wood-stoves, cookstoves and fireplaces emit high quantities of products from incomplete combustion compared to fossil fuel combustion (Loo and Koppejan, 2002). This is mainly caused by the use of natural draught which causes the incomplete combustion and methods of reducing this are not cost-effective (Loo and Koppejan, 2002).

Biomass may be a renewable energy source in the long term, but short term environmental issues are also evident. Deforestation is happening all around the world, with trees and in some cases even entire forests being logged for the wood. This unsustainable collection of wood is contributing to other natural disasters such as mud-slides, a loss of the watershed and desertification, all of which pose a greater risk to the human population both through primary risks and secondary risks such as pressure on agricultural productivity (GACC, 2013). A large number of replanting schemes are taking place across the globe but many areas will take decades to rejuvenate. An efficient cookstove should not only decrease the harmful emissions but can also reduce fuel consumption which in the long term will result in less trees being logged.

Global warming is becoming an increasingly greater issue to the human population, and emissions from poor combustion of biomass fuels is no different in contributing to this. Black carbon and methane are two products of cookstove combustion and although have short life spans still provide unwanted effects. Black carbon is known to contribute 25 to 50% of the carbon dioxide towards global warming whilst methane is the second most common greenhouse gas (GACC, 2013). Although CO$_2$ contributes approximately 80% towards global warming, methane has a global warming potential 3.7 times that of carbon dioxide (Lashof and Ahuja, 1990). It is therefore evident that the need for cookstoves to produce clean emissions is not only a health issue but a global environmental issue also.

### 2.6 Benefits

Many people will assume that those in LDCs cannot afford to use these clean cookstoves due to the initial costs. However, it is known that the poor do pay heavily in their health for their unsanitary facilities, suggesting that clean cookstoves will pay for themselves through health, economic and environmental benefits (Cordes, 2011). Unsanitary facilities and toxic emissions will result in a greater risk of illness and therefore greater medical expenses are needed. More fuel efficient cookstoves will result in using less fuel leading to less time collecting said fuel. Time spent fetching firewood could potentially be spent
earning money. However, the benefits of the most efficient cookstoves may not be as easy to implement. Pearce (2010) highlights that building a relationship with the users is just as important as introducing the technology. For some, although they dislike the smoke, it does in fact have a value in keeping away malaria-carrying mosquitoes and killing bugs which nest in thatched roofs (Pearce, 2010).

2.7 Efficiency Testing

2.7.1 Water Boiling Test

The water boiling test (WBT) which quantifies thermal efficiency, firepower and specific fuel consumption (Berrueta et al., 2007) is a standard efficiency test and will be used in this project. There are three stages to the WBT, a high power cold start, a high power warm start and a low power slow cook (Berrueta et al., 2007). The high power cold start tests how quickly the cold stove takes to boil a 2 litre pan of water at room temperature. The high power warm start follows this test as the stove is already warm. Again the time taken to boil a 2 litre pan of water at room temperature is recorded. These two tests will identify any differences in efficiency when the stove is cold and when it is warm. The final test uses a pre-weighed amount of wood after the high power tests and the 2 litre pan of water is kept simmering at 3°C below boiling for 45 mins. These tests will be used in this project as a measure of thermal efficiency and will be carried out for each set of experiments to gain further insight into the most efficient setup of the research furnace.

2.7.2 Other Tests

There are two other standard protocol tests, the controlled cooking test (CCT) and the kitchen performance test (KPT). These tests are more qualitative in that they require actually using the stoves to cook food. Therefore due to time constraints these two tests will not be carried out in this project.
Chapter 3

Equipment and Techniques

3.1 Fuel

Wood chips were the fuel used for experimentation. These wood chips were produced from Radiata Pine (*Pinus Radiata*) trees sourced from a timber processing plant in Jamestown, South Australia. The chips are produced by passing the pine pieces through a drum chipper. To achieve a consistent size, the pieces are passed through a 25mm screen. Those not passing through are reprocessed while fine particles (less than 2mm for any dimension) are removed from the process altogether. Pine bark also accounts for a small portion of the chips (less than 10%). A sample tested was found to include chips varying from $75 \times 25 \times 3 \text{ mm}$ to $8 \times 5 \times 2 \text{ mm}$ with the average size approximately $30 \times 20 \times 3 \text{ mm}$.

The moisture content of the chips was not directly taken prior to each test, however the majority of chips were taken from a batch which had previously been dried to achieve a moisture content of approximately 10%. A second batch was also needed after exhausting the first. This batch had a mixture of wet and dry chips and so 16 buckets were then laid out and dried for several days to achieve the moisture content of approximately 10%. As it is known that wood with a moisture content of greater than 60% is not acceptable, the moisture content of these chips was low enough to not cause further action.

3.2 Research Furnace

In 2013 a research furnace was commissioned to create a controlled environment which aimed to simulate that of the TLUD cookstove. In the real world the type of cookstove and type of fuel varies from region to region making empirical assessment only valid for each individual region. This therefore provides the reason for designing the research furnace. By providing a controlled environment, more detailed and accurate experimentation can take place. The furnace is able to control a number of variables including the primary air flow rate, secondary air flow rate, chimney height, height of fuel relative to secondary air and relative to chimney top as well as the chimney diameter. However, the furnace has not been completely tested and so this project aims to assess its suitability for testing wood combustion with forced primary and secondary air.
Figure 3.1: Schematic Drawing of Research Furnace

Figure 3.2 shows the Research Furnace prior to an experiment while Figure 3.1 shows an annotated schematic diagram. The labels indicate the main features of the setup which can be seen from the outside. The pot and pot stand were incorporated into the setup to assist with efficiency testing. The pot stand setup is explained in more detail in section 3.3.

**Primary Air Flow Rate**

The primary air (PA) flow rate can be controlled using the small fan situated on the outside of the furnace as can be seen in Figure 3.2. The PA flows into the base of the furnace first before being induced up through the mesh in which the fuel will be positioned and up out of the top of the chimney. The PA can be adjusted using a small pulse width modulator (PWM) with 5 positions. Figure 3.3 shows the five positions marked on the modulator and Table 3.1 shows the flow rate for each position using previous data obtained from (Boerema et al., 2013).

**Secondary Air Flow Rate**

The secondary air (SA) flow rate can be controlled at 12 locations around the top of the combustion chamber. At each location a long pipe is connected with a valve allowing the flow rate to be adjusted. The pipe is ‘long’ so that the flow will be symmetric across the diameter and will not bias results. The flow rate can be controlled using a standard flow...
3.2. RESEARCH FURNACE

Figure 3.2: Annotated Image of Research Furnace

Figure 3.3: Image of Primary Air Fan
Table 3.1: Primary air flow rate settings for each position (Boerema et al., 2013)

<table>
<thead>
<tr>
<th>Position</th>
<th>Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 L/s</td>
</tr>
<tr>
<td>2</td>
<td>8 L/s</td>
</tr>
<tr>
<td>3</td>
<td>10 L/s</td>
</tr>
<tr>
<td>4</td>
<td>22 L/s</td>
</tr>
<tr>
<td>5</td>
<td>22 L/s</td>
</tr>
</tbody>
</table>

meter which is situated upstream to the 12 pipes. By using the ABB Flow Calculator the flow was calculated to be 12.8 L/s using the pressure as 600kPa and the 3/4”-27-G-10/83 weight.

**Chimney Height**

The grey tube section above the combustion chamber is the chimney. The height of this chimney can be adjusted by simply moving the chimney up and down and measuring that the height is uniform around the circumference. Higgins et al. (2011) showed that the maximum burn rate occurred with a chimney diameter of 100% the fuel chamber diameter and a chimney height of 150% the fuel chamber diameter. This was therefore taken to be the basis for this project. The height of the chimney which protruded out from the fuel chamber was measured and set to be 150% of the diameter. The diameter was 205mm and so a height of 310mm was used. A line was marked onto the chimney so that it could be achieved for each experiment without the need to re-measure.

**Grill Height**

Inside the combustion chamber will lie the grill in which the fuel can be placed during testing. It is suspended by thin wires which hook over the top of the combustion chamber. The wires have negligible effect on the secondary air flow. The height can be altered by adjusting the length of the hooks.

### 3.3 Pot Stand

Three standard 4 litre pots were purchased for the water boiling test, these can be seen in Figure 3.4. Three pots were used to allow time for the pots to cool and be cleaned thus improving the efficiency of the testing procedure. A glass lid was also used with the handle removed thus providing a hole for the thermocouple. The handles on the pan were also removed to avoid them melting.

Methods for holding the pot at a set height above the chimney were discussed. A number of designs were drawn up which met the following specifications:

- able to adjust the height;
- able to be central over the chimney; and,
• able to rest in the same position for multiple experiments.

The design ideas included suspending the pot from the flue above, suspending the pot from a number of poles and building a stand for the pot to rest on which didn’t interfere much with the flow. It was decided that a pot stand would be the most reliable. As Figure 3.5 shows the stand is comprised of 4 vertical frame elements which have been fixed to the base frame for the furnace. Each frame element has a ledge at the top in which the pot can rest. These can be adjusted allowing for the height above the chimney to be altered.
3.4 Emissions and Efficiency Testing Equipment

3.4.1 Testo Gas Analyser

To measure the emissions produced a Testo\textsuperscript{TM}350 Flue Gas Analyser was used. This piece of equipment was able to measure the content of oxygen (O\textsubscript{2}), carbon monoxide (CO), carbon dioxide (CO\textsubscript{2}), nitric oxide (NO), nitrogen dioxide (NO\textsubscript{2}), nitric oxides (NO\textsubscript{X}), hydrogen (H\textsubscript{2}) and hydrocarbons (C\textsubscript{x}H\textsubscript{y}) (Testo, 2011).

This project not only focused on the harmful emissions produced but also how efficient the stove was as this would ultimately reduce fuel use and therefore emissions and would help reduce deforestation and other environmental issues.

3.4.2 K-type Thermocouple

The efficiency of the furnace was measured by carrying out a water boiling test (WBT). A K-type thermocouple was used to continuously measure the temperature of the water. From this point forward it will be referred to as the water thermocouple (TC). The tip of the water TC was inserted through a small hole in the top of the pan lid and made sure it was submerged in the water. A nut was adhered to the thermocouple at a set height in order to act as a stop for the thermocouple. This ensured the thermocouple was in the same position for each test. The other end of the thermocouple was connected to a data receiver which in turn connected to the computer.

3.4.3 Infrared Thermometer

An infrared laser thermometer was used to measure the temperature on the outside of the furnace chamber. A small circle was marked in chalk on the outside of the furnace for measuring the temperature in a consistent spot throughout testing.

3.4.4 Personal Protection Equipment (PPE)

PPE was required to be worn during all testing. This included safety goggles, a set of overalls, two pairs of gloves, and a breathing mask for handling wet wood chips and for unexpected smoking of the fuel.

3.5 Testing

3.5.1 Furnace Setup

To setup the furnace a number of tasks had to be performed beforehand to ensure it would remain in the same position throughout the entirety of the testing. The furnace was placed centrally below the flue hood to allow the fumes to leave the area as quickly
and efficiently as possible. The furnace was marked in position to enable visual feedback on its position. A risk assessment and safe operating procedures (S.O.P.) were created for safety. These can be seen in Appendix C.

### 3.5.2 Preliminary Testing and Familiarisation

For familiarisation of the furnace and equipment a number of small tests were conducted to understand the different variables and note the observations. These also helped to figure out timings and the correct procedure.

Initially, 500g of wood chips were weighed, using a set of scales with a resolution of 0.1g, placed in the furnace and burnt for 10 mins. The primary air was set to maximum (22L/s) and the secondary air was not used. Observations were that the flames were not huge, the occasional flame emerged above the chimney, the flames quickly died down to just embers and there were no blue flames. The remaining ashes were thrown away. The ring drawn on the outer cylinder was too low (below the fuel grill) and so another ring was drawn in chalk further up to obtain more accurate results.

The secondary air was then used at 40% (5L/s) with 500g of wood chips. The observations were that the flames were greater with the potential of secondary combustion occurring. The primary and secondary air were switched off after the peak flames and left to cool.

The pot stand was constructed and a water boiling test was carried out to calculate the maximum amount of water which could boil during the combustion time. Two litres of water was used for each experiment. Fresh water from the tap was used and was of approximately equal temperature throughout the different tests. The pot was positioned 120mm above the chimney and contained 2000g of water. The water TC recorded the continuous water temperature while the Testo recorded the emissions below the pot. With 500g of fuel, the water was far from boiling, peaking at 52°C, whilst using one kilogram the water peaked at 82°C. When the pot was lowered to a separation distance of 50mm, the 2000g of water boiled after approximately 7 mins.

The work of Higgins et al. (2011) and Boerema et al. (2013) showed they were able to obtain biochar. In an attempt to gain biochar, or more than just ash from the wood, the flame was starved of oxygen after four minutes by placing a metal sheet over the chimney. Unfortunately the furnace was not completely air tight and created dangerously high CO levels and smoke as can be seen in Figure 3.6.

### 3.5.3 Test Procedure for Varying Secondary Air

The first set of experiments looked at varying the secondary air flow rate and keeping all other variables the same. The chimney height was set at 310mm, pot separation distance at 50mm and primary air flow rate set at 22L/s. Four different tests were carried out, each repeated three times. The different secondary air flow rates used were 10% (1.28L/s), 30% (3.84L/s), 50% (6.40L/s) and 70% (8.96L/s). As the flow rates were determined by a float at a level judged by eye, and not measured directly, the exact flow rates could not be taken to as high a resolution as previously listed. The approximate values used were 1, 4, 6 and 9L/s. To account for slight atmospheric temperature differences throughout
the day, the order of tests on each day was altered. The detailed procedure for these tests is shown in Appendix B.

A trial test was always carried out to ensure the furnace started warm and at the same temperature throughout. For each experiment 1kg of fuel was used. For safety and for consistent timings throughout the experiments, the furnace was never touched, with or without protection, until the top of the cylinder was less than 100°C. After checking that the grill was level, the fuel was poured into the chamber ensuring that it was also level. The chimney was placed back into position, using the spirit level to ensure it was in the vertical position. Once the chimney was in position, the Testo probe was placed into its stand with the end of the probe positioned in the centre and directly level with the top of the chimney. The pot, containing 2kg of water, was placed onto the pot stand and visually aligned with the chimney to ensure the exhaust gases flowed evenly around the outside of the pot. A clean lid was added to the pan and the water TC was placed through the central hole. Checks to make sure all the cables and wires were plugged in and either covered up or out of the path of any stray embers.

A cap full of methylated spirits was poured into the furnace, covering as much of the fuel as possible. The extractor hood was turned on and checks to make sure all other connected vents were blocked was carried out. The fuel was lit using a rolled up piece of paper towel which was dropped into the furnace once the OCT was exactly 65°C.

The PA was turned on after one minute to its maximum (22L/s) and the SA was turned on to its pre-set value for the experiment. The OCT was recorded every 30 seconds, starting at 1.5 minutes, using the infrared thermometer. The experiments were conducted for 13 minutes with the SA and PA turned off after 11 minutes. The experiments were ran in...
a continuous cycle to ensure that the furnace always started at the same temperature, conveniently being pre-heated by the previous experiment.

### 3.5.4 Test Procedure for Varying Primary Air

The same procedure was taken for the second set of experiments where the primary air (PA) was varied. The secondary air (SA) was constantly kept at 50% (6L/s) and the PA was adjusted for all experiments. 9 experiments were carried out, three for each of the positions 2, 3 and 4 on the PWM dial. The flow rates were 8L/s, 10L/s and 22L/s respectively. Position 1 was not chosen as when the dial was turned to said position, the fan did not always turn on. Position 5 was not tested as the flow rate was very similar to position 4. Again, the order of experiments was mixed for each day to avoid atmospheric differences.
Chapter 4

Testing

The main aim of the project was to assess the suitability of the research furnace as an analogy to the real world biomass cookstove. By using pine chips as the fuel, systematic experimentation was conducted based on varying the primary air (PA) and secondary air (SA) flow rates. The research furnace is capable of varying both the PA and SA separately.

4.1 Varying Secondary Air

The 16 experiments were conducted with the primary air flow rate set to the maximum. This was to decrease the variability between experiments in the positioning of the dial for two reasons: the flow rate is greater and so a slight change in flow rate will have a smaller significance to the outcome, and the positioning of the dial is at the maximum and so the dial cannot be turned to a greater position. The order of experiments was varied to avoid any atmospheric differences in temperature throughout the day. This order can be seen in Table 4.1.

After the data collection process was complete, the data was organised into appropriate documents. Data regarding the emissions was transferred from the Testo program to a more user friendly program with the ability to manipulate the data. From this data, results for O₂, CO, FT and CO₂ were identified as important and chosen to be looked at more closely. The data was then sorted into those tests with the same SA for each of the four variables as well as for each specific category (e.g. CO) with varying SA. The arithmetic mean was found for each degree of SA and presented graphically for a number of variables.
Figure 4.1: Mean concentration of $O_2$ over four runs for different levels of secondary air

Figure 4.2: Mean concentration of $CO_2$ over four runs for different levels of secondary air
Figure 4.3: Mean concentration of CO over four runs for different levels of secondary air

Figure 4.4: Mean temperature of gases over four runs for different levels of secondary air
4.1.1 Oxygen

Oxygen ($O_2$) plays a key role in the combustion of biomass fuels. The content of oxygen in the atmosphere is approximately 21% which can be seen as the starting point in Figure 4.1. This value decreases for all levels of SA until it reaches a minimum at approximately 350s. It can be seen that there is a variation of about 5% $O_2$ for 10% and 70% SA respectively. This can partly be attributed to the higher SA causing a high amount of dilution but partly due to the increase in carbon dioxide through complete combustion. A lack of oxygen will cause incomplete combustion through a fuel-rich environment, as not all of the fuel can burn.

4.1.2 Carbon Dioxide

All biomass fuels will produce carbon dioxide which originates from the carbon content of the fuel. The $CO_2$ emissions from biomass combustion are often considered to be $CO_2$ neutral with regard to the reduction of greenhouse gases (Muench and Guenther, 2013).

Figure 4.2 shows that the % $CO_2$ for 10% is greater than that for 70%, with a difference of approximately 3% at peak values. This however disagrees with the statement in 4.1.3 which states that the higher the content of $O_2$ the lower the CO and higher the $CO_2$. This could potentially be due to the process of dilution between the secondary air and the Testo probe. With a higher SA there will be a greater ratio of air and hence an increase in $O_2$ percentage. This will dilute the mixture and the percentage of $CO_2$ will appear lower. However, this could cover up the true amount of $CO_2$ emissions and hence further investigations into the actual amount of $CO_2$ should be conducted.
4.1.3 Carbon Monoxide

Carbon monoxide is a major product of incomplete combustion. During the combustion stage, the CO oxidises to CO$_2$ if there is O$_2$ available (Loo and Koppejan, 2002). This is consistent with the results for O$_2$ and CO whereby the CO levels peak at a lower value for 70% SA (Figure 4.3) which corresponds to a higher value of O$_2$ also for 70% SA (Figure 4.1). Table 4.2 shows the minimum and maximum values for O$_2$ and CO respectively.

Table 4.2: Minimum and maximum values for O$_2$ and CO at different levels of secondary air

<table>
<thead>
<tr>
<th>Emission</th>
<th>10% SA</th>
<th>30% SA</th>
<th>50% SA</th>
<th>70% SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>% O$_2$ (min)</td>
<td>4.608</td>
<td>5.628</td>
<td>8.083</td>
<td>9.453</td>
</tr>
<tr>
<td>ppm CO (max)</td>
<td>11534</td>
<td>7079</td>
<td>4170</td>
<td>2950</td>
</tr>
</tbody>
</table>

4.1.4 Flue Temperature

Flue temperature (FT) is the term used by the Testo software to refer to the thermocouple measuring the temperature at the end of the probe. This was placed in geometrically the same position relative to the chimney and pot for each experiment so that the results would provide a comparison. However, each experiment produced a flame of different heights, which in the case of the natural draught experiments, reached the FT probe thus causing inaccurate readings of the emissions and temperature.

Figure 4.4 shows the mean temperature of the flue gas over time. It can be seen that when the SA flow rate of only 10% was used, the FT was considerably higher, up to 200°C greater than at 70% SA. This shows that the heat, and ultimately power, produced from combustion at lower SA flow rates is greater, leading to increased efficiency. This is because all experiments started with 1kg of fuel and lasted for approximately the same length of time, and so if higher temperatures are transferred to the pot then less fuel will be needed for cooking. This ties in with the water boiling test in Section 4.1.7.

It was also known that a possible reason for the decrease in temperatures at higher SA flow rates is attributable to the emissions being cooled down. Although it is possible for the same power and heat to be produced, the higher SA flow rate is unnecessary and is decreasing the efficiency.

4.1.5 Summary

In Figure 4.1 it can be seen that the initial percentage is approximately 21% which is representative of the O$_2$ percentage in air. This then decreases with time until it reaches a plateau at approximately 250 seconds. This can also be linked with Figure 4.2 which shows that while the O$_2$ is decreasing, the CO$_2$ is increasing steadily up until the same time (250s) where it also reaches a plateau. Between 250s and 450s both the O$_2$ and CO$_2$ have little variation. This links in with Figure 4.3, as for the period up to 450s the CO levels remain very low which suggests that from 250s to 450s, the fuel undergoes complete combustion. Further evidence for this lies in Figure 4.4. This figure shows
that the temperature in the Testo probe reached its maximum at approximately 250s and remained stable until approximately 450s.

At 450s the flue temperature (FT) in Figure 4.4 begins to decrease simultaneously with the CO$_2$ in Figure 4.2 along with the steady increase of O$_2$ in Figure 4.1. At the same time, the CO levels rapidly increase until they reach a peak just after 500s. All of this evidence leads to the knowledge that the complete combustion has finished and incomplete combustion has begun. It is this period of time which is the most dangerous with regard to the emissions produced.

### 4.1.6 Outer Cylinder Temperature

The outer cylinder temperature (OCT) was measured using an infrared thermometer. A laser is incorporated into the thermometer to assist with the location of the readings. For all measurements the laser was positioned inside a circle drawn on the outside of the furnace. The average results for each set of SA flow rate readings was calculated and graphed as can be seen in Figure 4.5. This graph shows that the peak in temperature for the 70% SA average is the greatest with the 10% SA average being the lowest. However, the range in temperature is only 50°C at the peak and the order does not remain constant over time suggesting that these results have little to show at the stage.

![Figure 4.5: Mean outer temperature over four runs for different levels of secondary air](image)

Figure 4.5: Mean outer temperature over four runs for different levels of secondary air
4.1.7 Water Boiling Test

The water boiling test is the main test for efficiency. A pot filled with two litres of water was used in each experiment with the temperature measured by a K-type thermocouple. This data was then averaged across each repeat to create Figure 4.6. It can be seen that the temperature variation is not great, however the temperature for 10% SA reaches boiling point (100°C) approximately 3 minutes before 70% SA. This helps to show that the 10% SA system is more efficient, especially when linked with the results from section 4.1.4 which show that the temperature below the pot is greater for 10% SA.

![Figure 4.6: Mean temperature of water over four runs for different levels of secondary air](image)

4.2 Varying Primary Air

The experiments for varying the primary air (PA) drew less conclusive results. Figure 4.7 is representative of all of the varying PA results. As the graph indicates, it is not clear which of the degrees of PA gives the greatest value nor the minimum as there is not much variation. A cause of this could be due to the dominance of the secondary air. The Testo probe which measures the emissions and flue temperature is placed in the flow downstream of the secondary air which suggests that by this point the secondary air may have diluted and cooled down the emissions produced. The graphs for varying primary air can be seen in Appendix E.
CHAPTER 4. TESTING

4.3 Natural Draft

The third and final experiment involved three tests:

1. using a natural draught in place of the primary air fan,
2. using a natural draught in place of the secondary air, and
3. using a natural draught for both the primary and secondary air.

The data for these tests were added to the graphs for the varying secondary air tests so that a comparison could be made as to whether the results were similar to fan forced combustion. Figure 4.8 shows these results for O₂. As can be seen, the results are very poor. The only result which didn’t reach 0% O₂ was with natural PA. The following problems give explanations on these results and those shown in Appendix F.

Maximum Levels Reached  During the second and third experiments, the Testo gas analyser reached the maximum recordable level for CO and H₂. The Testo could only record up to 50000 ppm (0.05%) for CO which was reached after only 2 minutes. The Testo then stops the flow of emissions into the system until they are lower which causes the spikes in Figure F.4. After approximately 7-8 minutes the program then stops recording so that it doesn’t damage the machine. As the emissions are dangerously high, this is obviously a major concern but could also help to explain the health statistics from the users of these cookstoves.
Figure 4.8: Concentration of O\textsubscript{2} for three natural draught experiments overlayed onto mean concentration of O\textsubscript{2} over four runs for different levels of secondary air.
Lack of Area The gap in the base of the furnace for the natural primary air was large enough to draw in sufficient amount of air for combustion to occur. The evidence is with the results for natural primary air given acceptable levels. In stark contrast, the gaps for the natural secondary air were not very large in comparison. This only provided a small area for the secondary air to be drawn into. This could provide a reason behind why the natural SA and natural PA & SA both gave invalid results. Increasing the SA area could perhaps provide a better insight into the suitability of this research furnace.

4.4 Summary

Having analysed the results for all three sets of experiments, conclusions based on the initial aims were given. The results indicate that the secondary air flow rate has an impact in following ways.

The higher the secondary air flow rate:

- the higher the $O_2$ in the emissions stream,
- the lower the CO emissions,
- the lower the $CO_2$ emissions, and
- the lower the efficiency.

It was unable to determine any conclusions from varying the primary air flow rate but the results from the natural draught indicate that:

- the secondary air inlets couldn’t induce enough air, and
- the emissions produced and the efficiency did not match those produced through the fan-forced approach.

This indicates that the research furnace is not a suitable analogy to the real world biomass cookstove in its present state. However, these types of furnace could still be used in the third world for larger industry based combustion needs, including schools, orphanges and blacksmith stables.

Although the research furnace is not a suitable analogy, the results which show dangerously high levels of CO when used under natural draft conditions do indicate this as a possible cause of the poor health issues.
Chapter 5

Outcomes and Future Work

This project has produced a number of significant results in relation to the aims which were identified at the beginning of the project. The commissioned research furnace was the basis for the three sets of experiments; varying primary air, varying secondary air and natural draught. These three sets of experiments produced appropriate data which has been analysed and from this, results and conclusions have been drawn up.

5.1 Outcomes

5.1.1 Varying Secondary Air

The first set of experiments involved varying the secondary air flow rate. Four sets of tests were conducted for each of the four levels of SA, 10% (1L/s), 30% (4L/s), 50% (6L/s) and 70% (9L/s). The emissions, outer cylinder temperature and water temperature were recorded for each test, collated and averaged to produce meaningful graphs for O$_2$, CO, CO$_2$, FT (Flue Temperature), OCT (Outer Cylinder Temperature) and WBT (Water Boiling Test) which can be seen in Appendix D.

Results from these tests indicate that the secondary air flow rate has an impact in following ways.

The higher the secondary air flow rate:

- the higher the O$_2$ in the emissions stream,
- the lower the CO emissions,
- the lower the CO$_2$ emissions, and
- the lower the efficiency.

Table 5.1 shows the collated peak (or min) values for each variable. Although not necessarily representative of the results themselves, they do give an idea of the variation.
Table 5.1: Minimum and maximum values for $O_2$, CO, FT, $CO_2$, OCT and WBT

<table>
<thead>
<tr>
<th>Emission</th>
<th>10% SA</th>
<th>30% SA</th>
<th>50% SA</th>
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<td>11534</td>
<td>7079</td>
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<td>823</td>
<td>741</td>
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<tr>
<td>% $CO_2$ (max)</td>
<td>9.29</td>
<td>8.71</td>
<td>7.32</td>
<td>6.55</td>
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<td>OCT ($^\circ$C) (max)</td>
<td>464</td>
<td>470</td>
<td>492</td>
<td>496</td>
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<tr>
<td>WBT ($^\circ$C) (max)</td>
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5.1.2 Varying Primary Air

The second set of experiments involved varying the primary air flow rate. Three sets of tests were conducted for each of the three levels of PA, position 2 (8L/s), position 3 (10L/s) and position 4 (22L/s). Again, the emissions, outer cylinder temperature and water temperature were recorded for each test, collated and averaged to produce meaningful graphs for $O_2$, CO, $CO_2$, FT (Flue Temperature), OCT (Outer Cylinder Temperature) and WBT (Water Boiling Test) all of which can be seen in Appendix E.

The results from these tests are inconclusive until further research is carried out. However, the results do indicate however that there was not much variation between the levels of PA which suggests that the SA is the more dominant flow rate with regard to the emissions and efficiency of the biomass combustion process.

5.1.3 Natural Draught

The third and final set of experiments involved using the natural draught for combustion. Only three tests were carried out due to the high concentration of CO, which was deemed to produce an unacceptable risk to the operator and equipment. The three tests were:

1. using a natural draught in place of the primary air fan,
2. using a natural draught in place of the secondary air, and
3. using a natural draught for both the primary and secondary air.

Appendix F shows the graphs for these experiments. However, to summarise these graphs it can be said that using a natural draught in place of the primary air fan was the only test in which combustion properly took place. For the other two tests, the CO and $H_2$ emissions were dangerously high which caused the Testo machine to stop recording, thus producing incomplete results. However, this did indicate the following:

- the secondary air inlets could not induce enough air, and
- the emissions produced and the efficiency did not match those produced through the fan-forced approach.

From these statements it was concluded that the research furnace is not a suitable analogy to the real world biomass cookstove in its present state. Larger industry based combustion needs could however have a use for this type of furnace where higher temperatures and
means of removing harmful emissions are present. This could include blacksmith stables, forging, or schools and orphanages.

Although the research furnace is not a suitable analogy at present, the results which show dangerously high levels of CO when used under natural draught conditions do begin to indicate this as a possible cause of the poor health issues of which further research must be undertaken.

5.2 Improvements and Future Work

After the completion of testing and analysis, it can be said that further understanding behind the process of wood burning in cookstoves is required. This project has produced meaningful results of which will provide the basis of further experimentation and research. Looking back, it is known that some aspects of this project have either not performed to expectation or need some improvement. The following sections look at these key improvement points and identify areas where future work should be carried out.

Location of Testo Probe

For this project it was decided to place the Testo probe in the centre of the chimney in line with the top. When this location was decided it was not known that should the flames reach this position then the Testo probe will not measure accurate readings of the emissions, merely the composition of the flame.

A factor which led to this decision was the fixation of the probe into a position which could be repeated and not move during the tests but able to be disassembled afterwards. A number of solutions were brought up including a large stand supporting the probe and suspending it from the flue. After discovering that it would be difficult to measure the distance to the centre of the chimney from far above, it was decided to construct a small probe stand. This was created using a series of clamps, clamped together, and as there was a lack of these, the stand was not very large. This combined with the higher probability that the stand would fall should it be made higher. As a result, the position of the probe in its current position was finalised.

In the future, the location of the probe should be discussed further prior to starting any experiments. The possibility of using two Testo probes in parallel could also be discussed to further the accuracy of the data.

Increase Secondary Air Inlet Area

As shown in the natural draught experiments, the research furnace was not a suitable analogy to the real world biomass cookstoves. One of the potential factors was the lack of secondary air. The 12 tubes which provide the secondary air have a very small cross sectional area which when converted to natural draught must only have a small flow rate if any at all. This therefore needs to be considered should the research furnace aim to implement the real world biomass cookstoves. One solution could be to increase the area
that the secondary air can enter the furnace. This could be achieved by removing the tubes and/or creating larger holes with removable plugs. Before altering the current furnace, it would be useful to gain exact measurements of the flow rate for both the primary air and secondary air.

**Increase Number of Repeats**

The first set of experiments had three repeats whilst the second set had 2 repeats and the final set had no repeats. This is definitely something which should be addressed in future projects. The sole reason behind lack of repeats was time constraints. Each experiment took almost one hour which only led to maximum four or five per day based on the laboratory hours and time for heating the machine up and clearing away equipment. Should methods of reducing the time for each test be discovered then this will help with increasing the number of repeats.

**Reducing Experimentation Time Frame**

Time was a major issue related to the lack of repeated data. One potential reduction could be by raising the starting temperature of the furnace. The temperature of 65°C was decided based on previous empirical testing. Whilst carrying out preliminary testing the temperature of the furnace when the next test was ready to be started was 65°C. Throughout the later experiments, there was a large proportion of time being wasted by waiting for this set temperature. This shows that the starting temperature could have been raised and saved approximately 10 mins per experiment. Although not much, over the course of 1 day this could result in an extra test. Should there be multiple people working on the project, the resulting time between experiments could be further reduced.

**Identify Other Key Emissions**

This project has analysed a small number of key emissions produced from the combustion of biomass fuel. Others including NO\textsubscript{x}, NO\textsubscript{2}, NO and H\textsubscript{2} could also be investigated to gain further understanding behind the complete and incomplete combustion of biomass and their implications on the environment.

**Other Key Variables**

This project only investigated the effects of varying the primary and secondary air flow rates. There are are number of other key variables which could be investigated. These include:

- the pot separation distance - varying this distance will affect the flow of the emissions and/or flame around the pot,
- the height of fuel with respect to the secondary air - this could affect the efficiency of the pot, either reducing it as the flow has cooled down or increasing it as further
combustion can take place. This could also identify if the furnace chamber is too large or too small,

- the height of the Testo probe relative to the flame height,
- the emissions produced across the width of the fumes,
- the emissions produced with increasing distance from the furnace - this could determine how much the emissions dilute with distance to the furnace and could potentially give a solution for reducing the health risks,
- the width of the chimney, and
- the height of the chimney.
Chapter 6

Project Management

This project has followed the previously amended timeline with relative success throughout the duration of the project. The timeline shown in Appendix A.1 shows that that project only began in late October. This was due to problems with the unsuitability of a previous project and consequently decisions were made following this which led to the commencement of a new project. Extensions for the project definition statement and plan, and mid-project report were kindly accepted. As much of the first semester was lost, it was decided that all experimentation would be conducted during the student summer holidays. The experimentation part of the project took longer than expected and so was continued into the start of the second semester. The lessons learned from this are to plan more time for experiments. Although the experiments continued for longer than expected, due to careful planning, this didn’t delay other tasks.

At the beginning of the project, the initial aims defined were to:

- assess the suitability of a cookstove furnace as an analogy to biomass cookstoves,
- experimentally assess emissions produced from the combustion of wood fuel for various primary air flow rates,
- experimentally assess emissions produced from the combustion of wood fuel for various secondary air flow rates, and
- experimentally assess emissions produced from the combustion of wood fuel of different batch volumes.

As the project progressed it was decided that the fourth aim was no longer relevant to this project and was no longer focussed on. The first three aims remained and it can be said that the project was successful in meeting them.

Throughout this project a number of key milestones were identified. These milestones shown in A.2 are:

- submit the Project Definition Statement and Plan,
- submit the Mid-Project Report,
- give a seminar,
- submit the Research Paper,
• submit the Final Report.

A budget of $1500 was allocated to this project. The only money spent for this project was the purchase of the three pans for the water boiling test and printing costs. These totalled $70 and hence the budget remaining at the end of the project was $1430.
Chapter 7

Conclusions

This project has discovered the severity of the need for clean cookstoves. With 3 billion people around the world relying on cookstoves for cooking, cleaning and heating and 2 - 4 million premature deaths per year it is evident that further research must be carried out. Using biomass as a fuel for combustion has been widely researched, as has the emissions produced from this combustion. However, specific research in aiming to reduce the harmful emissions and increase the fuel efficiency is so far limited.

A research furnace was the basis for the project and systematic experimentation was conducted to meet the aims of the project. A main aim of the project was to assess the suitability of the research furnace as an analogy to the real world biomass cookstove. To achieve this, wood chips were used as the biomass fuel and systematic experimentation was conducted which involved varying the primary and secondary air ratios. The emissions produced throughout each experiment provided detailed analysis behind the combustion of the fuel. A water boiling test was also conducted which enabled simultaneous analysis on the efficiency of the furnace. The fan forced primary and secondary air flow rates provided an understanding behind the furnace and the combustion of wood chips, however to assess its suitability for a real world cookstove, a natural draught replaced the primary and secondary air.

The results from these experiments indicate that the secondary air flow rate has an impact on the emissions produced and efficiency of the furnace. The experiments showed that the higher the secondary air flow rate, the higher the O\textsubscript{2} in the emissions stream, the lower the CO and CO\textsubscript{2} emissions and the lower the efficiency. The varying of primary air flow rate proved inconclusive and so further research in this area must be conducted. However, the change in primary air showed less variation which indicates that the secondary air is the more dominant flow rate with regard to the emissions and efficiency of biomass combustion. Using a natural draught approach gave limited physical results, however this proved that the research furnace was not a suitable analogy to the real world biomass cookstoves which rely solely on natural draught. The dangerously high levels of CO during natural draught combustion could be a potential cause of the poor health issues, however further research must be conducted to prove this.

Further understanding behind the process of biomass combustion in cookstoves is now required. A number of key areas for improvement have been highlighted. The location of the Testo probe must be discussed for suitability prior to starting any experiments. The
secondary air inlet area proved too small for inducing enough air and hence increasing this is an area which must be considered. The number of repeat experiments must also be increased, along with a reduction in time frame for the experiments, in order to minimise the inevitable variation in results for combustion. Other key variables must also be considered such as the pot separation distance, the height of the fuel in the furnace and increasing the number of emissions to be analysed.

This project has been successful in identifying that the research furnace is not a suitable analogy to the real world biomass cookstove in its present state. However, this type of furnace would be ideal for large industrial based combustion needs including, but not limited to blacksmith stables, other forging processes, schools and orphanages in the third world.
Bibliography


EPA. What is particulate matter, May 2014.


IEA. Key world energy statistics, 2013.


AG Testo. Testo 310 · Flue gas analyzer, 2011.


Appendix A

Project Timeline

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<td>25/10/13</td>
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<tr>
<td>Read previous projects, posters, journals, presentations</td>
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<td>25/10/13</td>
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<td>Experimental Work Plan</td>
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<td>Visit Thebarton Labs, take pictures of setup, equipment</td>
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<td>Plan experimental methods</td>
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<td>Decide on method of analysing results</td>
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<td>Submit Mid-Project Report</td>
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Figure A.1: Timeline of Project
Figure A.2: Extended Gantt Chart for Project
Appendix B

Experimental Procedure

1. Turn on Compressed Air and Drier
2. Position computer stand in close proximity to furnace.
3. Plug in Computer
4. Plug in Primary Air (PA)
5. Plug in Testo and attach all cables and tubes
6. Plug water thermocouple (TC) into computer
7. Weigh 1kg of fuel (Pine Chips) into a plastic bucket. Tip: use a second bucket to collect from bag and pour into first bucket *** From this point forward, avoid touching furnace due to hot surfaces
8. Once top of chamber is less than 100°C (use infrared thermometer), take the old ash out using gloves and replace grill (not applicable for initial test)
9. Using a torch, ensure the grill is level – there should be no huge gaps or misalignments
10. Tip the new weighed out fuel into furnace, making sure none is spilled
11. Using a torch, ensure the fuel is level
12. Replace chimney to desired level. Use a spirit level to ensure chimney top is horizontal
13. Position the Testo Probe into stand and ensure the tip of the probe is in centre of chimney and at the desired height
14. Place a clean pan onto scales and zero. Using another pan or other container, pour in 2kg of water
15. Place pan with water onto pot stand and check it is stable
16. Visually check pot is aligned with centre of chimney
17. Add a clean lid
18. Place water TC through centre of lid and ensure it enters the water
19. Ensure all loose cables and devices are covered up/away from potential embers
20. Connect Testo tubes and wires
21. Open Testo program and test it works with the device
22. Open program to read thermocouple data
23. Set required secondary air (SA) flow rate
24. When outer cylinder temperature (OCT) is 70°C at marked position, pour in 1 cap-full of methylated spirits
25. Ensure extractor is on
26. Turn off A/C if necessary
27. Prepare a rolled up piece of paper
28. When OCT reaches 65°C, light the paper and drop into furnace
29. Start the stopwatch, Testo program and water TC program
30. After 1 minute, turn on PA then SA
31. Record OCT every 30 seconds beginning at 1.5 mins
32. After 11 mins turn off SA then PA
33. Record OCT for 11.5, 12 and 12.5 mins
34. At 13 mins stop recording water TC and Testo
35. Turn back on A/C if necessary
36. Save files under useful titles
37. Close Testo program to stop clicking
38. Unplug the Testo tubes to let it breathe
39. Remove water TC from water ***Stages 40 – 42 not necessary if first experiment of the day
40. Taking a clean pan (empty water if necessary) place on scales and zero
41. Take lid off previous experiment’s pan and pour hot water into clean pan on scales
42. Pour hot water back into dirty pan and take to the sink to clean it
43. Remove recent hot water pan from pot stand and carefully place in tray, where it cannot be knocked over
44. Remove Testo probe from stand
45. Remove chimney from furnace
46. Repeat for each experiment
Appendix C

Safe Operating Procedure (S.O.P.)
and Risk Assessments (R.A.)
SAFE OPERATING PROCEDURE: TLUD FURNACE WATER BOILING TEST

LOCATION DETAILS
School/Branch: Mechanical Engineering

TASK/ACTIVITY
Operation of the TLUD Furnace – Water Boiling Test
Date: 06/02/2014

PREPARED BY

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>Liam Holden</td>
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<td>Cristian Birzer</td>
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<td>Richard Pateman</td>
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<td>Marc Simpson</td>
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HAZARD IDENTIFICATION
Risk Assessment Dated: 23/05/2013
Assessment Record 721

RISK RATING
Medium (20)

SAFE OPERATING PROCEDURE DETAILS

STOP

DO NOT OPERATE PLANT IF YOU HAVE NOT COMPLETED (1) THE COMPULSORY UNIVERSITY OF ADELAIDE OCCUPATIONAL HEALTH AND SAFETY INDUCTION COURSE, AND; (2) DO NOT POSSESS THE REQUISITE QUALIFICATIONS OR TRAINING FOR THIS PIECE OF PLANT.

Preparation – Work Area Check
- Ready access to and egress from furnace (min of 600mm clearance required)
- Area is free from grease, oil, debris and objects, which can be tripped over.
  (Use diatomaceous earth (“kitty litter”) or absorption pillow to soak up grease, coolant, oil and other fluids)
- Ready access to fire extinguisher.
- Extractor hood in working condition.

Personal Attire & Safety Equipment:
- Approved closed toe type shoes must be worn at all times.
- Approved safety spectacles/goggles must be worn at all times.

WARNING: Information regarding the safe use of this equipment is to the best understanding at time of publication.

Effective Date: 06/02/2014
Review Date: 05/02/2015
Version 1.1

Figure C.1: Safe Operating Procedure Part A
APPENDIX C. SAFE OPERATING PROCEDURE (S.O.P.) AND RISK ASSESSMENTS (R.A.)

SAFE OPERATING PROCEDURE: TLUD FURNACE WATER BOILING TEST

- Long hair must be confined close to the head by an appropriate restraint.
- Thermal gloves should be worn at all times.
- Heat apron when appropriate

Machine Pre-operational Safety Checks – Safety Precautions that MUST be Observed:
- Visual inspection of machine to verify it is in good operational order, ensuring no damage to any stationary or moving parts, electrical cords etc. Any unsafe equipment is to be reported to an authorised staff member and tagged out.
- All electrical devices to be safety tagged.
- Ensure all piping and valves are adequately sealed.
- Ensure lighting and power are switched on their respective main switches, where required.
- Be aware of other activities happening in the immediate area.
- Wear appropriate PPE.

Operation: Water Boiling Test

Furnace Preparation
- Ensure light and power is switched on at their respective switches.
- Ensure functionality of the extractor hood.
- Ensure furnace is clean and free from contamination, and the workspace is clear.
- Ensure required fuels, a stop watch or other timing mechanism, fire extinguisher and TESTO gas analyser are readily accessible.
- Ensure mains power electricity is outside of the splash zone – should dousing water be used.
- CAUTION: Pot stand may be hot from previous experiments.
- Ensure all pieces of pot stand are secured and bolts are tight.
- Ensure pot stand is level and secure in order to keep the pot stable. Test the stand is sufficient enough to hold a quantity of water beforehand.
- Select height for the fuel grating.
- Set the grating upon the bolts at the chosen setting. Ensure that remaining holes are closed with either bolts or insulating tape.

Benchmarking
- Place prepared fuel uniformly on the grate.
- A set quantity of Ethanol may be added to the fuel to assist with combustion.
- Replace flue
- Set the TESTO gas analyser at a consistent height above the furnace. Be aware of the elevated temperatures expected to be observed at this location.
- Fill pot with cold water to level required, then place in correct position on stand. Ensure stable.

Figure C.2: Safe Operating Procedure Part B
SAFE OPERATING PROCEDURE: 
TLUD FURNACE WATER BOILING TEST

- Activate the extractor hood to its minimal setting.
- If using thermocouple to measure the water temperature, ensure adequate heat shielding of the wiring and wear thermal protective gloves when doing so.
- Ignite the fuel using either wooden matches or a BBQ lighter. Start the timer to determine burn time.
- Visually ensure that combustion is occurring over entirety of the fuel source.
- Activate the gas analyser and data logger to measure emissions from the fuel.
- Allow the fuel to burn to completion. If the flame must be doused before complete combustion, use water or a snuff bucket. Should the flame continue to burn in an unsafe manner, use the fire extinguisher. Record the time at this point.
- Allow a period of at least a minute for the furnace temperature to recede.
- Collect the biochar that is produced during the combustion. This should then be stored in a sealed container to prevent contamination. A vacuum or similar can be used for collection.

Clean Up
- Shut down gas analyser and store appropriately.
- Remove hot water from stand with thermal gloves and leave to cool in a safe place within tray where nobody with access.
- Shut down the extractor hood.
- Once fully cool, clean the furnace combustion chamber using the vacuum. Ensure to remove any traces of contamination that may interfere with future testing.
- Clean up surrounding area.

General Safety
- NEVER LEAVE THE TLUD FURNACE OPERATING WHILST UNATTENDED.
- Visual inspection of equipment prior to use. Unsafe equipment to be tagged out and reported to Workshop Manager.
- Only authorised qualified staff may operate this furnace, or students who have received full Competency Training from an authorised qualified staff member (recorded in training register).
- PPE to be worn at all times including: safety goggles, closed toe shoes, thermal gloves, and a heat apron.
- Long hair to be tied back.
- Douse flame using the snuff bucket or water before leaving it unattended.

NOTE: This Safe Operating Procedure must be reviewed within 1 year of date of issue or:
- a. After any accident, incident or near miss;
- b. When training new staff;
- c. If adopted by new work group;
- d. If equipment, substances or processes change;

Figure C.3: Safe Operating Procedure Part C
## Risk Register

**Location** The University of Adelaide - Fac of Eng, Comp & Math Sci - School of Mechanical Eng - Thebarton - The Factory 10/Store House 11 - FAC - *Level G - Lab - Burner / Flame testing

### Assessment Category: Tasks - General

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<td>OHS</td>
<td>General</td>
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<td>Room</td>
<td>FAC</td>
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<tr>
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<td>The Factory 10/ Store House 11</td>
<td>*Level G</td>
<td>Lab</td>
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<tr>
<td>Room Type</td>
<td>Item / Activity</td>
<td>Burner / Flame testing</td>
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### Assessment Record: 721

#### Hazard: * Explosion / Fire hazards

**Hazard Description/Nature of Risk**: Is there a potential for a person to be injured by an explosion or fire? e.g. ignition of surrounding area, using naked flame, gas, vapour, grain silos, chemical incompatibility, shock sensitive chemicals, chemical stability.

**How can this hazard/threat cause an incident/adverse event?**

- Gas leak from burner or transfer hoses.

**Residual Assessor**

- Medium (20) Richard Craig (Mech Eng)

### Risk Assessment Keywords

- Gas leak

### What controls are currently in place?

- SOP requires operator to check for leaks within system before flame operation.
- SOP requires operator to be near fuel isolation valve at all times.
- Ensure access to fire extinguishers and blankets.
- Ensure access to emergency services.

### Actions Description

<table>
<thead>
<tr>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost</th>
<th>Progress/Notes</th>
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</tr>
</thead>
<tbody>
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</table>

#### Hazard: * Exposure to gas (asphyxiants)

**Hazard Description/Nature of Risk**: Is there the potential for a person to be exposed to gas causing oxygen displacement? e.g. diesel emissions, liquid N, dry ice.

**How can this hazard/threat cause an incident/adverse event?**

- Irritation or damage to the respiratory system of the operator

**Residual Assessor**

- Medium (12) Andrew Crowe

### Risk Assessment Keywords

- Breathing, gas, fumes, smoke, pollutants, particulates, air

### What controls are currently in place?

- Extractor hood, well ventilated area

### Actions Description

<table>
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<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Contact with hot object or friction burn</td>
<td>Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? e.g. steam, naked flame, laser beams, heating block</td>
<td>Burn from hot burner nozzles. Burn from naked flame.</td>
<td>Medium (10)</td>
<td>Richard Craig (Mech Eng)</td>
</tr>
</tbody>
</table>

**What controls are currently in place?**

SOP describes continued use of cooling air after experiment to cool heated components. SOP instructs operators to stand away from the burner before and after flame ignition. Ensure access to cool running water for first aid treatment of burns.

**Risk Assessment Keywords**

<table>
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<tr>
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<tr>
<td>* Contact with chemicals, fumes or gas</td>
<td>Is there the potential for a person to come into contact with chemicals or gas? e.g. fumes from chemicals, dry ice, machine oils, Liquid N2</td>
<td>Cause irritation to the naked body and burns over exposed area, respiratory problems</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**What controls are currently in place?**

Extractor hood, safety goggles, ventilated area.

**Risk Assessment Keywords**

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<tr>
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<tr>
<td>* Contact with hot object or friction burn</td>
<td>Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? e.g. steam, naked flame, laser beams, heating block</td>
<td>Severe burns over exposed areas on the body.</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
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</table>

**What controls are currently in place?**

Safety Gloves, Coveralls, Safety goggles

**Risk Assessment Keywords**

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<tr>
<td>* Contact with stationary object</td>
<td>Is there the potential for a person to run or bump into a stationary object? e.g. knock their hand on a wall when pushing a trolley</td>
<td>Might possibly cause a fracture of a severe bruise. Cause other components to come loose exposing the operator to other risks</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**What controls are currently in place?**

Adequate lighting, safety tape on the ground

**Risk Assessment Keywords**

Object, physical injuries
## Appendix C: Safe Operating Procedure (S.O.P.) and Risk Assessments (R.A.)

<table>
<thead>
<tr>
<th>Hazard</th>
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<th>Cost Progress/Notes</th>
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</tr>
</thead>
<tbody>
<tr>
<td>* Explosion / Fire hazards</td>
<td>Is there a potential for a person to be injured by an explosion or fire? e.g. ignition of surrounding area, using naked flame, gas, vapour, grain silos, chemical incompatibility, shock sensitive chemicals, chemical stability</td>
<td>severe burns</td>
<td>Residual</td>
<td>Assessor</td>
<td>Andrew Crowe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### What controls are currently in place?
- Well ventilated areas, extractor hood, fire extinguishers within reach
- Fire, explosion

### Risk Assessment Keywords
- * Exposure to biological hazards
- Animal dung, bio waste

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</tr>
</thead>
<tbody>
<tr>
<td>* Exposure to biological hazards</td>
<td>Is there the potential for a person to be exposed to biological hazards? e.g. human or animal body fluids, infectious waste, cultures of micro-organisms</td>
<td>irritation on skin or body parts</td>
<td>Residual</td>
<td>Assessor</td>
<td>Andrew Crowe</td>
<td></td>
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</tbody>
</table>

### What controls are currently in place?
- Safety gloves, Safety goggles, Adequate clothing
- Animal dung, bio waste

### Risk Assessment Keywords
- * Other
- Burner tipping over: causes burns or fire within laboratory.

### What controls are currently in place?
- SOP requires operator to be near fuel isolation valve at all times.
- Burner fixed to ground using heavy weights or bolts.

### Risk Assessment Keywords
- * Exposure to hot environment
- Heat stress or dehydration from extended exposure to flame

### What controls are currently in place?
- SOP instructs operators to stand away from the flame during operation.
- All experiments are of short duration to reduce exposure time.

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SOP instructs operators to stand away from the flame during operation.
All experiments are of short duration to reduce exposure time.
Access to potable water for re-hydration.

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<tr>
<td>* Slips, trips or falls</td>
<td>Is there the potential for a person to slip, trip or fall? e.g. slippery, uneven or cluttered work surfaces, plant location, lack of safe guards such as rails</td>
<td>tripping over fuel / air supply piping/hoses</td>
<td>Richard Craig (Mech Eng)</td>
<td>Low (4)</td>
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**Risk Assessment Keywords**

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<tbody>
<tr>
<td>* Contact with sharp object</td>
<td>Is there the potential for a person to be cut, stabbed or punctured by a sharp object? e.g. knife, sharp or pointy edge objects, flying or moving objects</td>
<td>Cuts on exposed areas on the body.</td>
<td>Andrew Crowe</td>
<td>Low (4)</td>
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**Risk Assessment Keywords**

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<tbody>
<tr>
<td>* Environmental hazards</td>
<td>Is there a possibility of generating significant environmental hazards? e.g. energy/water consumption, hazardous waste/ emissions</td>
<td>possible cause for poisoning due to contact or inhaling gas/waste emissions.</td>
<td>Andrew Crowe</td>
<td>Low (4)</td>
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Figure C.7: Risk Assessment Part D
<table>
<thead>
<tr>
<th>Hazard Description/Nature of Risk</th>
<th>Hazard</th>
<th>Assessment</th>
<th>Residual</th>
<th>Low (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overstress - manual handling and ergonomics</td>
<td>Is there the potential for a person to be exposed to manual handling injury through reaching, bending, lifting, pulling, pushing or repetitive motions?</td>
<td>Severe strain on body, body sprain.</td>
<td>Severe strain on body, body sprain.</td>
<td>Severe strain on body, body sprain.</td>
</tr>
<tr>
<td>Risk Assessment Keywords</td>
<td>What controls are currently in place?</td>
<td>Alternate heavy lifting duties</td>
<td>Alternate heavy lifting duties</td>
<td>Alternate heavy lifting duties</td>
</tr>
<tr>
<td>What controls are currently in place?</td>
<td>Having enough rest, keeping hydrated and eating enough food.</td>
<td>Alternate heavy lifting duties</td>
<td>Alternate heavy lifting duties</td>
<td>Alternate heavy lifting duties</td>
</tr>
<tr>
<td>Actions Description</td>
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Figure C.8: Risk Assessment Part E
Appendix D

Varying Secondary Air Results

Figure D.1: Mean concentration of $O_2$ over four runs for different levels of secondary air
APPENDIX D. VARYING SECONDARY AIR RESULTS

Figure D.2: Mean concentration of CO over four runs for different levels of secondary air

Figure D.3: Mean temperature of gases over four runs for different levels of secondary air
Figure D.4: Mean concentration of CO$_2$ over four runs for different levels of secondary air

Figure D.5: Mean temperature of outer cylinder over four runs for different levels of SA
Figure D.6: Mean temperature of water over four runs for different levels of SA
Appendix E

Varying Primary Air Results

Figure E.1: Mean concentration of O

2 over three runs for different levels of primary air
APPENDIX E. VARYING PRIMARY AIR RESULTS

Figure E.2: Mean concentration of CO over three runs for different levels of primary air

Figure E.3: Mean temperature of gases over three runs for different levels of primary air
Figure E.4: Mean concentration of CO$_2$ over three runs for different levels of primary air

Figure E.5: Mean temperature of outer cylinder over three runs for different levels of PA
Figure E.6: Mean temperature of water over three runs for different levels of PA
Figure F.1: Mean concentration of O₂ for natural draught overlayed onto secondary air
APPENDIX F. NATURAL DRAUGHT RESULTS

Figure F.2: Mean concentration of CO for natural draught overlayed onto secondary air

Figure F.3: Mean temperature of gases for natural draught overlayed onto secondary air
Figure F.4: Mean concentration of CO₂ for natural draught overlayed onto secondary air

Figure F.5: Mean temperature of outer cylinder for natural draught overlayed onto SA
Figure F.6: Mean temperature of water for natural draught overlayed onto SA