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一种新型户用采暖炉具结构优化及其排放性能研究

Research on the Structural Optimization and Emissions Performance of a New Model Household Heating Stove

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Research on the Structural Optimization and Emissions Performance of a New Model Household Heating Stove

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FOR

MASTER’S DEGREE

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Statement of originality

I hereby declare that the materials, methodologies and the results presented in this thesis are purely original. Information derived from published and unpublished works of others has been duly acknowledged and cited in the reference list. The thesis has been written as a partial fulfillment of the requirement for the Master's degree in Agricultural Engineering at China Agricultural University. I accept that China Agricultural University has the copyright of the material herein.

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摘要

由于固体燃料（例如生物质和煤）的不完全燃烧，全球每天大约 30 亿人暴露在空气污染之中。其结果是一氧化碳（CO）和颗粒物（PM）等燃料不完全燃烧产物能够引起或加剧呼吸道疾病，导致数百万人过早死亡。在蒙古国首都乌兰巴托市，煤炭是炊事和取暖的主要能源。由于燃烧效果差，乌兰巴托已经成为世界上污染最严重的城市之一。

本文设计一种新型反烧式炉具（TJ4.0），对其热性能、排放性能进行了研究，并与中国一种典型的正烧式炉具（取自河北省某炉具制造企业）的性能进行了对比研究。TJ4.0 反烧式炉具的操作方式和顶部点火的正烧式炉具一样，均可以在燃烧过程中添加燃料，但是颗粒物排放较少。而传统正烧式炉具在燃烧过程中燃料直接加在燃烧层顶部，会产生大量的颗粒物排放。燃料种类和粒径大小、燃烧室类型和操作方式均会影响热效率和一氧化碳、颗粒物、二氧化碳等的排放水平。

与使用散煤（未分类）和半焦化型煤（60mm）的正烧式炉具相比，使用半焦化型煤（16-25mm）、小块散煤（16-25mm）、和大块散煤（25-40mm）的 TJ4.0 反烧式炉具在不完全燃烧过程中产生的排放明显降低。TJ4.0 采暖炉具在给定的 6 小时测试过程中扣除背景值后的 $PM_{2.5}$ 平均值为：半焦型煤 0.03±0.04 mg/MJ，小块散煤 0.11±0.03 mg/MJ，大块散煤 0.2±0.42 mg/MJ。TJ4.0 采暖炉具对应以上三种燃料的热效率分别是 90.7±3.96%，93.1±1.34%和 85.4±0.57%。

反烧式采暖炉和正烧式采暖炉相比，在燃烧散煤时，产生的细颗粒物和 CO 等污染物分别降低 96%和 95%；在燃烧型煤时，产生的细颗粒物和 CO 等污染物分别降低了 99.5%和 86%。

关键词：采暖炉具，结构优化，热效率，细颗粒物，在线测试

Abstract

Approximately 3 billion people world-wide are exposed to the emissions daily because of the incomplete combustion of solid fuels such as biomass and coal. The result is the release of products of incomplete combustion including carbon monoxide (CO) and particulate matter (PM) causing or inflaming respiratory diseases leading to the premature death of millions. In the Mongolian capital city of Ulaanbaatar, coal is main source of cooking and heating energy for half population. Because of the poor quality of combustion, the city is one of the most polluted capital in the world.

This paper designed a new model cross-draft stove, studied its thermal performance and emission performance, and compared the results of this stove with Chinese typical up-draft stove (sample was taken from a manufacturing enterprises in Hebei province) burning different types of fuel. TJ4.0 cross-draft stove is operated same manner as a top-lit up-draft ignition method. In this stove the fuel can be refuelled while in operation, without risking a burst of high PM emissions, whereas the up-draft stove is a ‘batch’ process which generates large quantities of PM emissions if refuelled from above. Carbon monoxide, particulate matter, carbon dioxide and heating efficiency were determined from the variations of fuels, combustors and operational properties.

Emissions formed from incomplete combustion were significantly lower for the TJ4.0 cross-draft stove compared with the up-draft (Chinese typical space heating and cooking stove) using different fuels: semi-coked raw coal briquette (16-25 mm), small raw coal (16-25 mm) and large raw coal (25-40 mm) in the cross-draft stove and raw coal (unsorted), semi-coked coal briquette (60mm) in the up-draft stove. In six-hour test sequence, background $PM_{2.5}$ was subtracted from the emitted mass in each case, and the TJ4.0 stove emitted on average, 0.03±0.04 mg $PM_{2.5}$ per MegaJoule burning semi-coked coal briquette, 0.11±0.03 mg/MJ for small raw coal and 0.2±0.42 mg/MJ for large raw coal. The thermal efficiency for the TJ4.0 stove was found to be 90.7±3.96%, 93.1±1.34% and 85.4±0.57% respectively for the three fuel types.

The cross – draft stove compared with the up-draft, $PM_{2.5}$ and CO pollutants were produced less by 96% and 95% in raw coal and when burning the semi – coked coal briquette, these particulate emissions were lower 99.5% and 86% than the up – draft respectively.

Key words: Heating Stove, Structure Optimization, Thermal Efficiency, Particulate Matter, Online Testing

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Chapter 1 Introduction

This chapter introduces an overview of space heating stoves and solid fuel use in Mongolia, China and other developing countries, and presents air pollution issues, health and environmental challenges. The significance of the research is stated, and the specific research objectives are presented. An overview of the thesis layout is given at the end of this Chapter.

1.1 Background

In the world, approximately three billion people use solid fuels such as coal, crop residues and woody biomass as their main source of household energy for cooking and heating (Shen et al., 2014). A majority of these households are located in rural areas of both developing and developed countries (World Bank, Asia Sustainable and Alternative Energy Program, 2013). Solid fuels including coal will continue to be used as the dominant energy source for electricity generation and industrialisation (Finkelman et al., 2002). The inefficient combustion of solid fuels is the primary source of air pollutants such as carbon monoxide (CO), volatile organic carbons (VOC), particulate matter (PM), black carbon (BC) and polycyclic aromatic hydrocarbons (PAHs) (Boman et al., 2005, Bignal et al., 2008). These emissions not only cause severe air pollution which are harmful to human health, causing chronic respiratory diseases, pneumonia, and cardiovascular, immune and nervous system problems. It also has an adverse impact on the atmosphere and climate change (Shen et al., 2012). Particulate matter, known as PM defined by US EPA, is a mixture of tiny particles and liquid droplets suspended in the air. It comprises multiple components such as acids, organic chemicals, metals and soil or dust particles. Particulate matter, especially that having an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$), is of concern to scientists and the public due to its quantified effects on human health such as increased risk of morbidity and mortality from cardiovascular and respiratory diseases and an elevated attribution of premature death (Ling et al., 2015).

If $PM_{2.5}$ is deposited deep in the lungs, it can be health-damaging. It was demonstrated that if the particles enter rapidly into the human circulatory system, the lung is affected and at the same time, the number of particles in the blood will be increased and thereby increasing exposure of other organs (California Environmental Protection Agency, 2003). Particulate matter produced from the incomplete combustion of solid fuel is rich in toxic organic pollutants such as PAHs. (Shen et al., 2011). Emission factors fluctuate significantly depending on the type and size of fuel, combustion device and operation conditions, air supply and cold zones in the combustion chamber and even the test method (Shen et al., 2012, Glasius et al., 2008, Anenberg et al., 2013). However, most smoke is emitted during the ignition sequence and smoke concentrations drop drastically once flames are observed (Lloyd, 2014) or during refuelling when some of the physical conditions prevailing during ignition are replicated. During the late stages of a fire when the flames decrease, PM emissions may disappear entirely while CO usually rises with falling fuel bed temperatures. Stoves fitted with a chimney limit the negative effects of emissions on household indoor air quality (IAQ) (Lloyd, 2014).

This thesis aims to make a systematic investigation of the advantages, if any, of cross-draft space heating stoves and to compare performance of this stove type with a typical commercial top-lit up-draft heating stove as used extensively within China. A set of combustion experiments were performed under controlled laboratory conditions using different combinations of fuels and stoves. Carbon monoxide, particulate matter, carbon dioxide and heating efficiency were measured for each stove-fuel combination.

1.2 Use of Space Heating Stoves and Solid Fuel in the World

According to the Technical Report of the World Bank, "*The State of the Global Clean and Improved Cooking Sector"* (World Bank, 2015), at least 4.3 million premature deaths annually and 110 million disability-adjusted life years (DALYs) are attributed to stove-related household air pollution (HAP). Therefore, reduction of domestic stove emissions is crucial to addressing this public health issue in areas that rely on the appliances using solid fuels as their source of heating and cooking energy.

Despite such programs, many households still rely on inefficient stoves for cooking and heating because they cannot afford to purchase improved stoves or they prefer the services provided by their traditional stoves.

Around the world, there are many types of solid fuels, including wood, coal and agricultural residues that are used as energy carriers for cooking and heating, because of availability, cost effectiveness or custom, rather than modern energy carriers such as electricity or gas. According to the Indian National Census (2001), 75% of households in India use solid fuels (primarily firewood and cow dung) in rural areas, where about 70% of total population lives. It is estimated that there are 400,000 deaths caused by acute lower respiratory infections in children and 34 000 deaths from chronic obstructive pulmonary diseases in women (Balakrishnan et al., 2011). In Dublin, many households switched to coal for heating and cooking because of the oil price increases in 1980 (Lockwood et al., 2009). In South Africa, the majority of coal is used for electricity generation; however, poorer households in the interior that are located close to coal mines use coal as the predominant domestic energy source during winter (Balmer, 2007). There are many types of solid fuels including wood and coal used as an energy carrier for cooking and heating.

In China, coal provides approximately 70-75% of primary energy needs and more than 700 million people still rely on solid fuels for cooking and heating. The majority of them live in rural areas (Asia Sustainable and Alternative Energy Program 2013, Millman, 2008). The National Bureau of Statistics (2006) reported that the use of coal for cooking varies greatly depending on the geographic region. Some 19% of homes in Eastern China, 38% in Central China, 27% in Western China, and 7% in Northern-eastern China use coal. About 65% of all households use coal for space heating in Shaanxi, Hubei and Zhejiang Provinces

(Sinton et al., 2004). It is estimated that HAP from solid fuels results in more than a million premature deaths each year in China. China is one of the few countries that promotes the dissemination of improved cookstoves and has household energy policies that promote improved cooking and heating solutions (Asia Sustainable and Alternative Energy Program 2013). Between 1982 and 1992, the Chinese National Improved Stoves Program (NISP) which has been described as the "World's largest publicly financed initiative to improve stoves". It introduced 180 million improved biomass and coal stoves in rural areas, and more than 100 million of these are still used. NISP is one of the most successful stove programs. China since 1980s, according to a survey by (Li et al., 2009), the energy consumption of Northern China represents 56% of total energy use in China and more than 80% of rural energy consumption is for heating.

The Clean Stove Initiative – China (CSI-China) is a collaborative effort by the Chinese Government and the World Bank that aims to expand access to clean cooking and heating stoves for poor, primarily rural households. Launched in 2012, CSI-China is part of the East Asia and Pacific (EAP) CSI which includes country-specific programs in Indonesia, Mongolia, and Lao PDR as well as China. It provides a regional forum for knowledge-sharing. The CSI-China reflects the World Bank's shared commitment with the Chinese Government to bring clean cooking and heating solutions to all of the country's citizens by 2030. China's Energy Agency estimates that by 2030, 280 million of their citizens will still rely on solid fuels for cooking and heating (Asia Sustainable and Alternative Energy Program 2013).

In Ulaanbaatar city, Mongolia, lignite is the largest source of home heating energy used during the heating season. Ulaanbaatar is located 1,300 meters above sea level and is the coldest national capital in the world. The temperature in January is often -35°C to -40°C. Due to the increased energy demands of a rapidly growing economy and population, PM concentration were among the highest in the world (Gunchin et al., 2012). Air pollution in winter is largely caused by coal burning in *Ger* stoves[1] and domestic low-pressure boilers. These appliances are used in permanent settlements in extensive areas of the city known as *Ger districts*. In the 2009, air pollution statistics of Asian cities, Ulaanbaatar City ranked highest for $PM_{2.5}$ during the winter months. This demonstrates a clear need for government intervention to reduce emissions, intending to improving human health and the environment. In 2013 the national and city governments introduced the Ulaanbaatar Clean Air Project (UB-CAP) to replace Ger stoves. This resulted in a dramatic 65% reduction in the level of $PM_{2.5}$ in Ulaanbaatar city in Mongolia. (Ulaanbaatar Clean Air Project, 2015).

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[1] "*Ger*" refers to the traditional round, felt tent used as a portable residence by nomadic Mongolian people.

1.3 Pollutants produced from the solid fuel combustion

1.3.1 Pollutants

Flue gases are gases that produced by burning fuel. Exhaust occurs as a gas because of high temperature during the combustion process, but there can also be liquid droplets and solid particles in the exhaust (James, 2006). Many different organic compounds are formed from incomplete combustion. For instance, PAHs are produced in the flame when hydrocarbons polymerise instead of oxidising and also form from incomplete cracking (decomposition) of complex cyclical or long chain pyrolytic compounds (Flagan and Seinfeld, 1988). When a fuel containing hydrocarbon burns, the exhaust gases include water (hydrogen + oxygen) and carbon dioxide (carbon + oxygen). The exhaust gases can include carbon monoxide (CO), oxides of nitrogen NO_x (nitrogen + oxygen) and, if sulphur is present in the fuel, sulphur dioxide SO_2 (sulphur + oxygen). (Mandal, 2012).

Carbon dioxide and some of the products of incomplete combustion such as carbon monoxide, methane and particulate matter contribute to radiation forcing in the atmosphere and hence to climate change. If biomass is harvested sustainably, the CO_2 formed due to combustion will theoretically be reabsorbed by the biomass growing to replace it. However, if equivalent biomass is not constantly regrown, the CO_2 from biomass will contribute to the net atmospheric burden of greenhouse gases (Kumar et al.,2013). Carbon monoxide is a product of incomplete combustion, generated prolifically in combustion conditions in which there is insufficient oxygen to complete combustion to CO_2. CO is a colourless and odourless, and is highly toxic substance, acting by impairing the oxygen-carrying capacity of the blood. If CO concentrations are higher than 35 ppm, it is considered unacceptably hazardous to human health. Above this limit it can cause headaches, dizziness, loss of consciousness and ultimately death (James, 2006).

Determining and controlling the concentration of O_2 in the exhaust stack is one of the most critical parameters for ensuring complete combustion. The oxygen in the atmosphere is constant (20.9%). O_2 reading in the exhaust stack should be monitored for the lowest excess air compatible with complete combustion, and to control the level of CO in the stack (James, 2005). As it is not practically possible to attain complete fuel combustion with the exact stoichiometric amount of oxygen, there is always some excess required. The practical guideline for optimum combustion conditions is frequently set at 13% excess O_2 at standard temperature and pressure.

These various factors affect the dependent variable that is particulate matter emissions. In addition, these variables are strongly associated with each other. For instance, if the stove is poorly designed or if the users cannot afford to operate their stove with the optimum fuel, it may enhance particulate matter emissions. This pollutant is harmful to human health and the environment. The whole system must be evaluated to determine the efficiency of the system. Fire grates and chimneys enhance the ventilation conditions. Except when adding fuel, the door of the fuel hopper or the refuelling opening should be closed – this prevents the reverse flow of smoke through the stove door into the living space. Flue gases are disposed from the stove through a chimney to the outside, preferably well above ground level. If the stove has natural ventilation, the draft is formed by chimney fuel combustion. The pressure of external air at the base of the chimney is higher than at the top – this small pressure difference induces the flow of air into the stove and out of the flue. Moreover, when the operator ignites the fire, they should give attention to optimal proportions of ignition material, fuel added and air regulation into the burner, as the starting fire may be smothered and smoke due to unfavourable ignition conditions.

1.3.2 Pollution hazard

During combustion, some toxic emissions or exhaust gases such as carbon monoxide, sulphur dioxide, nitrogen oxides, and particles are created from fuels and oxidant (TSI, 2002). Indoor air pollution from solid fuels is a significant harmful for low birth weight and acute respiratory infections which account for a remarkable 7% of the global burden of disease and it belongs to a class of infections that result from a wide range of viruses and bacteria (Desai et al., 2004, Naeher et al., 2000).

Particulate matter emitted from combustion contains hazardous components including heavy metals, arsenic, mercury, PAHs as well as many other substances which are harmful to the environment and human health. The health depends on particle size and composition. For example, larger particles (d_p>10 μm) tend to deposit in the airways and smaller particles (d_p<1 μm) penetrate to into the lung (Orange et al., 2012). The effects of the pollutants formed from the combustion of solid fuels have received significant consideration, especially in countries where people use heating and cooking appliances (Nussbaumer, 2001). Arsenic is during combustion of bituminous coals and anthracites containing the element. Hyper-pigmentation, hyper-keratosis, Bowen’s disease and squamous cell carcinoma are symptoms of arsenic poisoning (Zheng et al., 2005). A certain amount of arsenic can come from tainted foods and ingestion of dust containing high levels of pollutant (Finkelman et al., 2003). Fluorine volatilized from the combustion of domestic coal causes fluorosis, a disease affecting bones and teeth. Symptoms of this disease include “corrosion of tooth enamel (dental fluorosis), osteosclerosis, limited movement of the joints and outward manifestations such as knock-knees, bowlegs and spinal curvature” (Finkelman., 2003). There are extensive cases of this disease in the Guizhou province in China. Stone coal contains selenium. Selenium exposure is attributed to the emissions of combustion, and the use of coal ash as a soil amendment, resulting in crops taking up elevated amounts of selenium. Symptoms of selenium poisoning include fatigue, hair and nail loss (Zheng et al., 2005).

Breathing CO is dangerous, especially for pregnant women, the elderly, and people with heart or respiratory disease and PM can lead to mortality (Maccarty et al., 2011). Women and children are more affected by pollutant emissions because they spend prolonged periods close to or tending the stove (Levin et al., 2005). There is evidence that people who use the appliances as energy for cooking and heating for long periods daily are three times more susceptible to chronic obstructive pulmonary diseases such as chronic bronchitis that people who use the appliance with electricity and cleaner fuels (Dutta K et al., 2007). Types of diseases related to the use of biomass and solid fuels can be divided into respiratory and non-respiratory diseases. Respiratory diseases include the upper and lower respiratory infection, chronic obstructive lung disease, tuberculosis, lung cancer and asthma. For the non-respiratory diseases, it consists low birth weight and infant mortality, cardiovascular diseases, nasopharyngeal and laryngeal cancer and cataract diseases (Kumar, 2013).

Therefore, there exists a need to replace inefficient cooking and heating devices with efficient, clean burning appliances. Also, such campaigns could contribute to protecting human health and the environment, together with reductions in deforestation and greenhouse gas emissions. Moreover, there is a need to increase the knowledge of family members about health effect due to biomass and solid fuels combusted in cooking and heating appliances.

1.4 Combustion Process

In the book "*Combustion Analysis Basics*" (TSI, 2002), combustion processes are described as involving both physical and chemical processes to generate heat and light derived from the reaction between oxygen in the air and fossil fuels such as natural gas, fuel oil, gasoline or coal. Coal is a highly variable fuel that has a broad range of heating values, and variable proportions of carbon, hydrogen, oxygen, sulphur and nitrogen. In addition to the generation of thermal energy and the products of complete combustion, burning of fossil fuels may result in the emission of toxic substances.

Heating value, and volatile compound, moisture and ash content are critical measurements characterising these fuels. The heat value of the fuel is formed from the complete combustion of a unit quantity of fuel. It is expressed by the higher or lower heating value (HHV and LHV). HHV is the amount of heat produced by a unit of fuel is complete combusted, in calculating the heat spent to evaporate the water from the combustion of moisture and hydrogen in the fuel. LHV is the heat from a unit of fuel burned without calculation of neither the heat for evaporation of moisture nor the heat for gases is generated (Mandal, 2012).

When a fuel, initially at ambient temperature, is heated in the combustor, the moisture in the fuel particles must be evaporated before the heated and dried fuel can begin to combust. This process continues until the moisture completely driven off. The fuel lumps may fragment into multiple particles during the drying process due to the rapid expansion of moisture contained in the porous structures of the fuel. The process of heating and drying is an endothermic reaction in which there is net heat transfer into fuel particles (Miller & Tillman, 2008). When the fuel moisture is driven off enough, the fuel temperature increases and volatile hydrocarbons are vaporised. During this process, termed pyrolysis, the fuel components begin to hydrolyse, larger organic molecules begin break up (termed cracking) and oxidise. Many gaseous and liquid products are released from the fuel particles, including volatile and semi-volatile organic compounds, further water, methane, hydrogen and oxides of carbon (Tissari, 2008). Volatile oxidation involves initiation, propagation and termination chain in the combustion process (Miller & Tillman, 2008).

1.4.1 Complete Combustion

Combustion efficiency is a metric that expresses how well the fuel is burned (TSI, 2004). The critical parameters for efficient combustion are high combustion temperatures, adequate air supply, proper mixing of air and fuel gas, and sufficient residence time in the high temperature zone (Tissari, 2008).
Combustion efficiency is expressed as a ratio of the energy released as heat e to the total heat potential of the fuel (Eq. 1-1). The combustion efficiency is derived from a measurement of the stack heat losses as shown in the formula below:

$$\%\eta = 100\% - \left(\frac{\text{stack heat losses}}{\text{fuel heating value}} \times 100\%\right) \quad \text{(Eq. 1-1)}$$

Stack loss is wasted heat depending on the volume flow, stack temperature, flue gas composition and moisture released. Some losses are unavoidable in stove and boiler operations, as heat generated natural draft is required to drive air flow through the combustor (TSI, 2004).

1.4.1.1 Combustion temperature

In a combustion chamber, the oxidation reactions and combustion are more complete and proceed more rapidly at higher temperatures. The thermal mass, thickness, insulation and surface properties of the material used in the combustion chamber are parameters that affect the combustion temperature (Van Loo & Koppejan, 2008). Combustion efficiency and temperature are relatively higher, and heat losses reduced by insulation of the combustion chamber (Tissari, 2008). The thermal storage of ceramic materials, for example in rocket elbow stoves, and brickwork in boilers and cast-iron coal stoves, enable higher combustion temperatures to be maintained (Makonese, 2014).

According to Van Loo and Koppejan (2008), combustion temperatures are decreased by vaporisation of the fuel moisture, using energy from the fire, and this phenomenon slows the combustion process.

1.4.1.2 Mixing of air and fuel gas

The fuel gas should be well mixed with sufficient oxygen to allow complete oxidation of the fuel within the combustion chamber. Supplied air more than the amount theoretically needed for complete combustion is termed as *excess air*. Excess oxygen is the amount of oxygen in the incoming air not used during the combustion process. The excess air in its simplest form can be calculated as:

$$\%EA = \frac{(O_2 + 1/2 + CO)}{209500 - (O_2 + 1/2 \times CO)} \times 100 \qquad \text{(Eq. 1-2)}$$

$$\%\lambda = EA + 100\% \qquad \text{(Eq. 1-3)}$$

Where, λ can be used to calculate an emission factor (EF) for gases or particles in samples measured at the same time. The dilution of the sample by transient air makes no difference to the resulting EF provided the dilution is relatively steady, and the instruments have the same response time (Pemberton-Pigott et al., 2009). Additional excess air supplied to the combustion chamber results in its poor combustion efficiency and wastes fuel by cooling the combustion mixture because the air absorbs heat and transfers it out via the exhaust flue. Insufficient mixing in the combustion chamber may also lead to increased emissions of products of incomplete combustion. Excess air should be controlled to achieve significant fuel savings and optimum combustion efficiency (TSI, 2004).

1.4.2 Inefficient Combustion

Inefficient combustion results in poor combustion efficiency at reduced combustion temperatures. PM emissions tend to be greater when burning fuel with high moisture and volatile matter content, or with insufficient air supply. Fuel moisture contributes considerably to reducing heating of fuel because some part of heat from the combustion is spent to evaporate fuel moisture. Also, when the fuel contains high moisture and sulphur, internal surfaces in the burner and exhaust stack may occur due to the formation of sulphuric acid (Mandal, 2012).

1.4.2.1 Soot particles

Soot is generated under conditions combining insufficient combustion air with low flame temperature when solid and liquid fuels are burned. If an excess of cool air enters the combustor, it will reduce the overall temperature of the combustion gases, potentially leading to the formation of more soot particles. Excess soot influences in internal heat transfer surfaces and further impairs to the thermal conductivity (TSI, 2004). Soot forms under fuel-rich conditions in which hydrocarbons are incompletely cracked, rather than being fully oxidised to CO_2 and H_2O (Wiinikka , 2005). The complex hydrocarbons in the fuel break down into smaller pieces which may then react with another one to form PAHs droplets or particles. Soot particles increase by surface reactions and coagulation. PAHs compounds are joined to the surface of core particles by surface reactions (Bockorn, 1994, Tissari, 2008).

1.4.2.2 Ash particles

Ash is the waste, non-volatile product of fuel after the carbon components of fuel are completely burned. Ash volume and characteristics of the fuel are essential for use in the energy sector. When fossil fuels containing high ash content are combusted, at high velocity the ash contributes to surface erosion, and at low velocity leads to accumulation on the surface of the combustion chamber, heat exchanger or exhaust flue. The heat transfer from combustion to heat exchanger is thereby decreased, and the stack temperatures are increased. Eventually, thermal efficiency can be lower because of ash accumulation on the burner surface. Moreover, ash carried out with flue gases adversely affects the environment. The heating value and combustible part of the fuel are decreased in inverse proportion to the ash content (TSI, 2004). Ash particles in the combustion gases are called fly ash (Flagan & Seinfeld, 1988); ash retained in the stove is termed bottom ash.

Ash content is primarily from the original mineral (non-carbonaceous) content of the fuel. Mineral particles may pass through the process unaltered, or undergo physical and chemical alteration. Even high melting point compounds such as SiO_2 may be chemically modified in alternating reducing or oxidising conditions during combustion. Potassium in the fuel is quite reactive, and tends to be enriched in the fly ash component, forming compounds such as potassium hydroxide (KOH), potassium carbonate (K_2CO_3, potassium sulphate (K_2SO_4) and potassium chloride (KCl) (Christensen et al., 1998).

1.5 Significance of the Research

It has been estimated that *ger* households with traditional stoves consume on average 4,2 tons of coal and 3,2 tons of wood each year to meet their heating and cooking needs in Ulaanbaatar city of Mongolia. These households use nearly 550,000 tons of coal and more than 400,000 tons of wood during the heating season (Lobscheid et al., 2012). Atmospheric levels of PM in the ger areas of Ulaanbaatar city are high during the heating season, caused by traditional stove emissions and adverse atmospheric inversion conditions For example, the 24-hr PM_{10} concentrations measured in the winter exceed 3,000 $\mu g/m^3$ on occasion and monthly average $PM_{2.5}$ and PM_{10} concentrations during the 2008-2009 heating season exceeding 1,500 and 1,800 $\mu g/m^3$, respectively (Lobscheid et al., 2012). The Mongolian Government started the Ulaanbaatar Clean Air Project (UB-CAP) project with the aim of reducing ambient air pollution. The project involved distributing 45,000 energy efficient and low emission stoves to the households of six Ger districts in the city. Qualifying stoves were tested in the first half of 2013. The traditional ger stove thermal efficiency is 53%. Improved stoves supported by the UB-CAP had to be 70% efficient or greater. $PM_{2.5}$ produced per delivered Megajoule (MJ) of heat had to be reduced by 90% measured against the traditional ger stove.

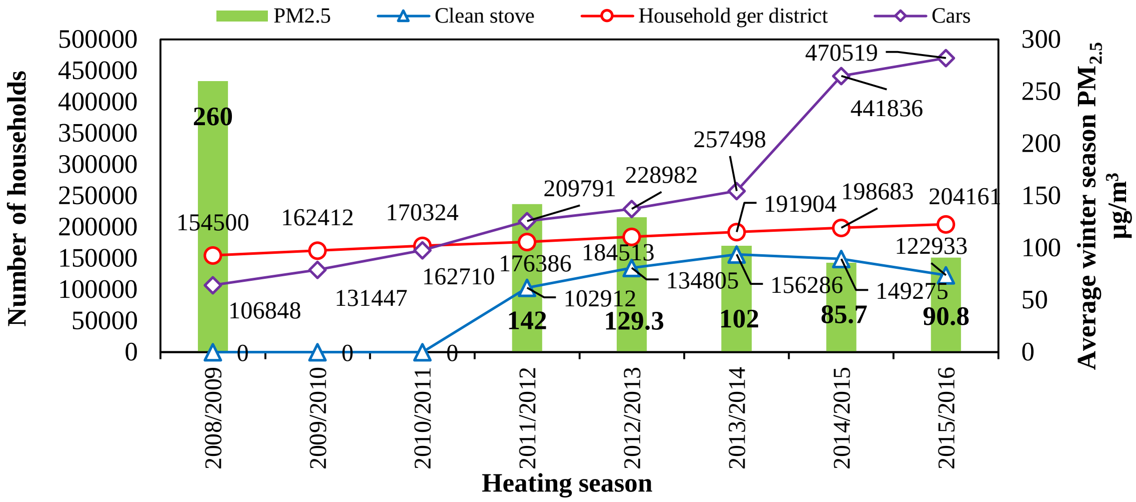


Figure 1-1: Stove program impact and air quality in Ulaanbaatar city, Mongolia (Ulaanbaatar Clean Air Project 2013).

Figure 1-1 shows the implementation and $PM_{2.5}$ results of Ulaanbaatar Clean Air Project. Following the distribution of low-emission stoves, ambient concentrations of $PM_{2.5}$ in Ulaanbaatar city decreased by 65%, from an average winter season 260 µg/m3 to 90.8 µg/m^3, despite a 24% increase in the population between 2008 – 2016, from 154,500 to 204,161 households. Over the same period the number of cars increased by 77%, from 106,848 to 470,519 vehicles (Ulaanbaatar Clean Air Project, 2013). This evidence indicates that vehicles contribute a minor amount to the ambient $PM_{2.5}$ concentrations in relation to the other dominant sources.

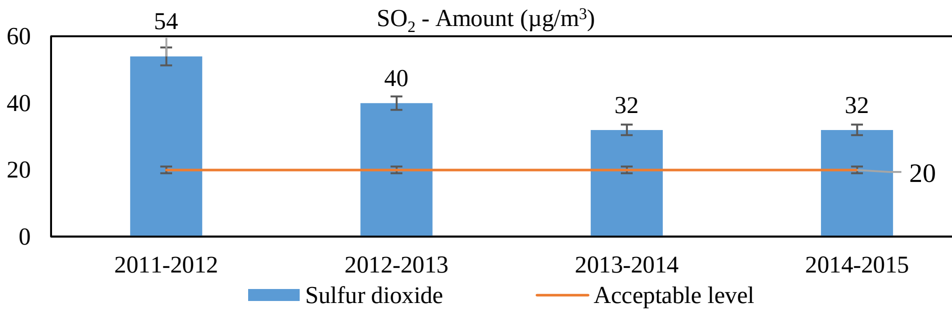


Figure 1-2: The air quality change in amount of SO_2 µg/m^3 in Ulaanbaatar city, Mongolia

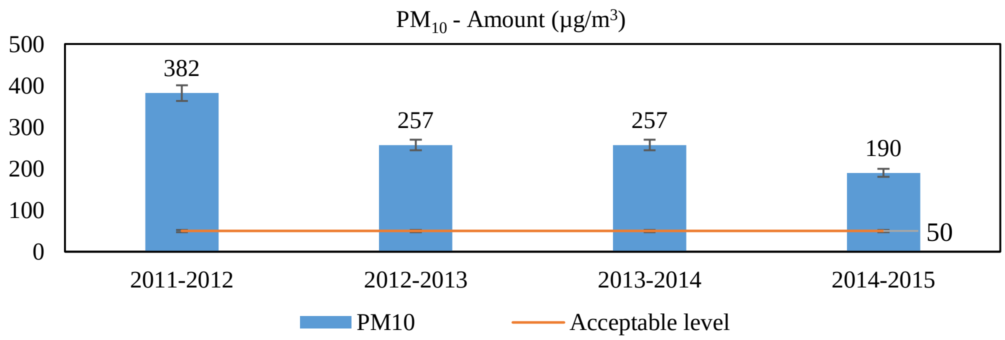


Figure 1-3: The air quality change in amount of particulate matter PM_{10} µg/m^3 in Ulaanbaatar city, Mongolia

The result shows that SO_2 and $PM_{2.5}$ were decreased, but according to the WHO Air Quality Guidelines, 2005 (WHO, 2005), the pollutants were still not reduced to acceptable levels (Figure 1-2 and Figure 1-3). Air pollution continues to be an urgent issue because the population and numbers of domestic heating and cooking appliances have increased sharply in recent years. The population growth increases demand on the power plants and increases the number of lower pressure boilers (LPB), vehicles and space heating stoves. In the winter, the air pollution level is still extremely high. More than half of all households are located in ger districts, and they continue to use domestic stoves for heating and cooking. Consequently, emissions from domestic solid fuel combustion remain the biggest contributor to air pollution in the Ulaanbaatar city.

Hebei Province is located in the north-east of China and there are the most polluted seven cities in this province. Rural households in western and northern China predominately depend on solid fuels. This province is a main area for manufacturing, including the energy-intensive heavy industry, and is a major source for fine particulate of air pollution which is known to have the impacts on public health. China's coke production accounted for more than 60% of the world, of which 14.5% was produced in Hebei. The air pollution in Hebei Province has aroused wide public concern. The air pollution burden of the southern Hebei area is particularly heavy because of it is surrounded by the other three populated and industrialized provinces, Shandong, Henan and Shanxi. The emission factors from coal contributes half of the air pollution in Hebei Province of China. The steel, coke and cement productions of the four neighbored provinces are as large as 40.8%, 50.1% and 22.6% of the national total amount. PM is the most important pollutant from coal burning in Hebei cities. Visibility and haze frequencies in Hebei cities are discussed, that Hebei has both the highest number of haze days and the most rapid growth in haze frequency in recent years (Wang et al., 2013).

Table 1-1: Test results for baseline stoves burning raw coal and semi-coked coal briquette

Fuels	Heating efficiency (%)	$PM_{2.5}$ (mg/MJ)	CO(g/MJ)
Semi-coked coal briquette	68.6	8.7	17.0
	73.6	4.1	39.4
	57.2	4.7	4.3
	62.8	1.0	4.9
Raw coal	63.3	33.2	3.1
	51.7	148.6	3.9
	65.4	2.2	5.5

Clean Air Project in Hebei province, China (2016)

The performances for the baseline stoves in Hebei province are showed in Table 1-1. As the results, $PM_{2.5}$ emissions from raw coal are higher on average by 2.2-148.6 mg/MJ than burning semi-coked coal briquette (1-8.7 mg/MJ). For CO emissions, when burning semi-coked coal briquette, it was emitted higher on average by 4.3-39.4 g/MJ to compare with the raw coal. The heating efficiency was delivered at similar level for both fuels in these stoves between 51.7-73.6% on average. During the ignition time, the pollutants are emitted more compared with other stages such as pyrolysis and high power at the whole testing sequence. If the kindling is ignited badly, it influences in the results of the emissions for whole sequence. Therefore, it is necessary to begin properly the fire, however there are many factors affect to the emissions from the combustion.

Air pollution from the combustion of solid fuels is big issue in both Mongolia and China, especially in the Ulaanbaatar city and in Hebei province. The coal is the main source of their energy needs for heating and cooking. Fuel type and stove design influence largely on the emission. Therefore, it needs to investigate the different type of stoves and its contribute to decrease the problems associated with air pollution in these areas.

Table 1-2: Problem statement of the study

Problem statement	Explanation
Universal statement	There are many cities around the world with poor air pollution.
Regional statement	Ulaanbaatar and Hebei Province are among the worst, despite clean air initiatives.
Local statement and problem to be addressed	Assuming that coal will continue to use as a major domestic fuel, need for cleaner burning stoves using this widely available fuel source.
What is the contribution that this thesis will make to address the problem?	The proponents claim this design has better energy efficiency and greater reduced PM and CO emissions. Hence the task in this thesis is to evaluate the performance of this new stove and compare it with a traditional, widely used model of a Chinese domestic coal stove as the baseline reference device.
Subsidiary objectives	The new device is intended for use in named cities, where the coal is the major energy carrier for domestic cooking and heating. Hence, two major remaining variable affecting performance are (a) the choice of either coal or semi-coked coal briquettes, and (ii) the size of the coal lumps.

The emission factors reported are functions of on fuel type, combustion conditions, flame temperature, air supply, fuel moisture, composition and concentration of combustion reactants and even the test method. Emission factors vary according to the stove design as well as operational practices and maintenance (James, 2006). Consequently, it is important that the stove design should be efficient and effective with lower emissions.

Therefore, it is crucial to test the influence of different designs and fuels, and their effect on emission factors. Hence, the continuing need to investigate different kinds of stoves to mitigate the problems associated with air pollution and further human health.

1.5.1. Research objectives

The main purpose of this study is to investigate effects on PM emissions from up-draft and cross-draft space heating stoves using different types of fuel. The emissions from a popular coal burning Chinese top-lit up-draft (TLUD) space heating stove and a cross-draft coal gasifier (TJ4.0) will be reported. The specific objectives of the study are to:

- Determine the thermal efficiency of each stove-fuel combination.
- Measure and determine pollutant emission factors for $PM_{2.5}$ and CO formed when burning different kinds of fuel in the TJ4.0 cross-draft stove;
- Determine emission factors for and conventional Chinese typical up-draft stove;

This investigation attempted to answer the following questions from the objectives:

- What the space heating efficiency of each stove-fuel combination is produced?
- What effect the different fuel types have on PM and CO emissions and combustion quality in the TJ4.0 cross-draft space heating stove?
- What the emission factors for the Chinese typical up-draft stove are formatted?

1.5.2. Research Design

The research design is presented diagrammatically in Figure 1-4:.

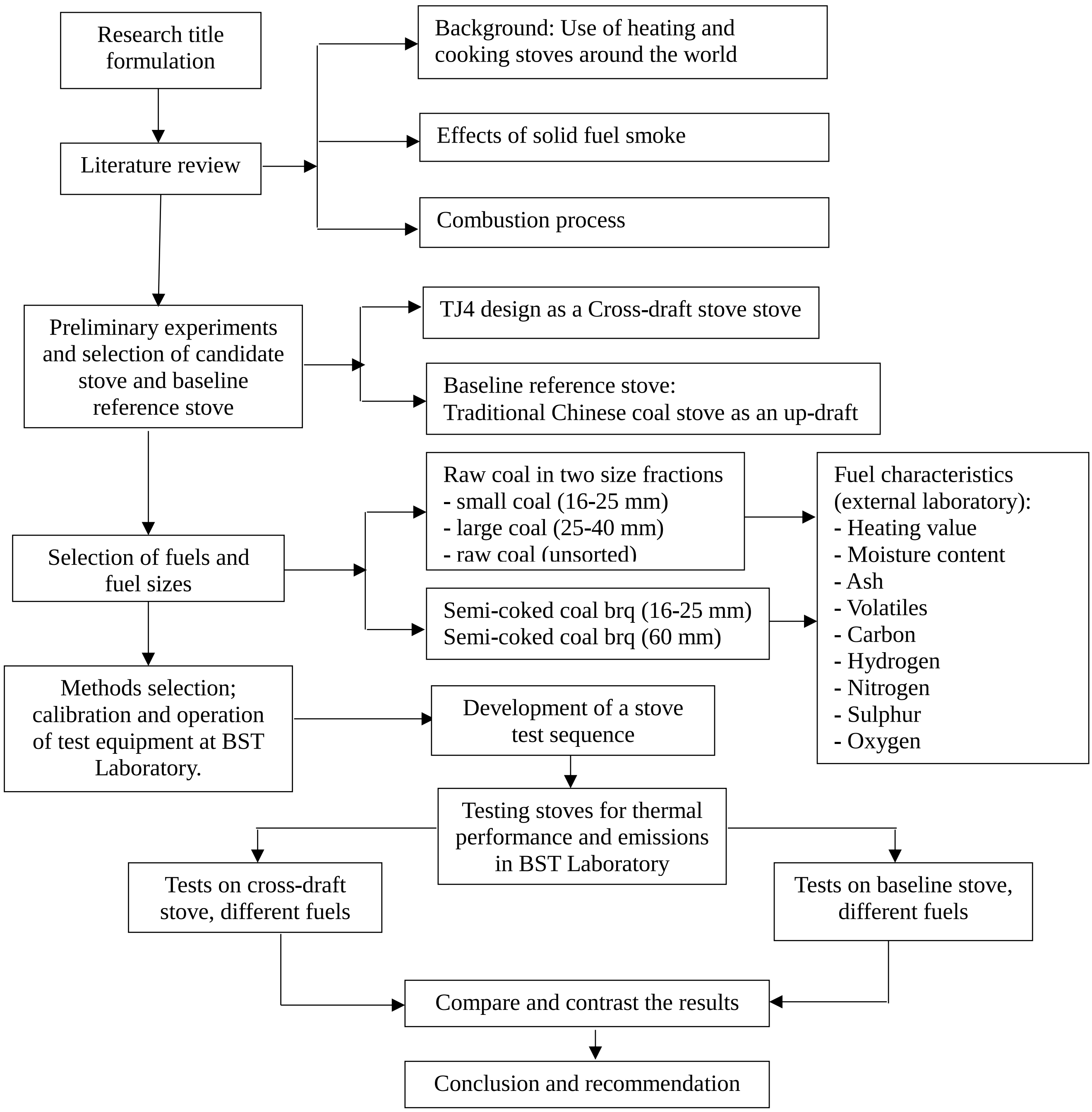


Figure 1-4: Research design and flow chart of technical route

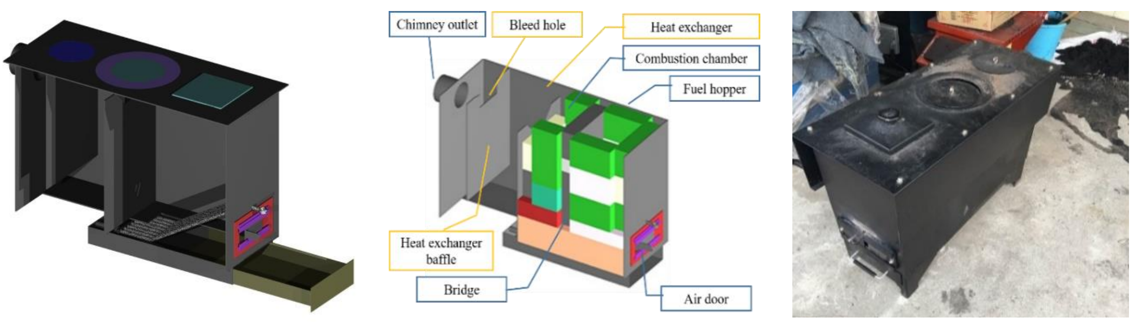
Chapter 2 Structural design, optimization of the TJ4.0 cross-draft stove and performance testing method

This chapter presents details of the description and structural design for the TJ4.0 cross-draft stove tested in this study. Testing method is given.

2.1 Structural design of the TJ4.0 cross-draft stove

In this research, the TJ4.0 stove as a cross-draft stove and Chinese typical stove as an up-draft stove were tested by burning different types of fuels. Tests were conducted under laboratory conditions. TJ4.0 design selected as a cross-draft combustor was tested for energy performance, emissions and particles. The structure of the stove is shown Figure 2-1. The stove body is made with 4.0 mm steel sheet. It comprises a fuel hopper, a cross-draft pyrolysis zone on a metal grate, a combustion chamber, a heat exchanger, chimney, hopper, ash drawer, covers for the cooking station and an air control door. The grate is sloped at 30° to allow the coke bed and fresh fuel to slide forward under gravity as the burning fuel shrinks and is combusted. The fuel hopper, coke bed and combustion chamber are surrounded and insulated ceramic bricks which can tolerate high temperatures. The TJ4.0 cross-draft stove design which is selected for this study has the following design elements:

- 4.0 mm mild steel sheet body and heat exchanger
- Ash drawer – 340×450×2 mm steel sheet
- High density, high temperature firebricks – 229×110×64 mm
- Grate – 468×160 mm, sloped at 30°
- One cooking station and one water heating station
- Cover plates for the pot holes and fuel hopper
- Chimney 108 mm diameter
- Air controller door



a. Side view without bricks b. Side view with bricks c. Assembled TJ4.0 stove

Figure 2-5: Design of the TJ4.0 stove as a cross-draft

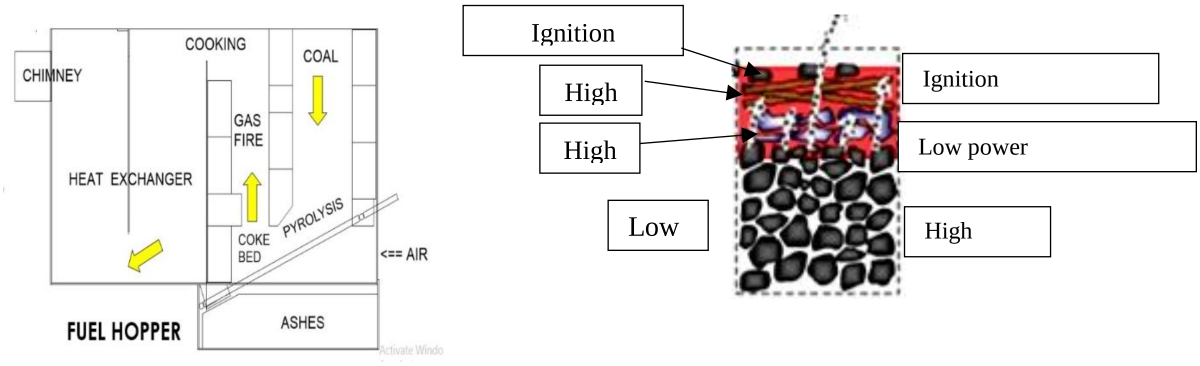
Inside bends are sharp. Chimney connector is 90×300 mm, rolled and welded. The leg height is to suit local customer preferences. The bricks are placed in loose (not cemented) for service by the customer. Door hinges: 2×10mm bullet hinges welded on the right side. The Door latch is on the left and the door must seal all round against the stove body. The design of this stove is shown in Figure 2-1.

The design includes some specific instructions to allow the stove to be assembled correctly, and to control inlet air only through the air controller. Inner corners of the fuel hopper and combustion sections should be sharp, so that the bricks may be inserted flush against the steel surface. The chimney connector is 90 ×300 mm, rolled and welded. The chimney height should be 2 to 3 m. The leg height is optional to suit local customer preferences. The bricks are placed in loose (not cemented) for service by the user. The door hinges are 2×10 mm bullet hinges welded on the right side. The door latch is on the left. The door and fuel hopper lid must seal against the stove body. The top plate of the stove is bolted to the body with an airtight, temperature resistant gasket to prevent air inflow or leaks of combustion gases into the room (Pemberton-Pigott, 2016).

2.1.1 Fire lighting methodologies

The cross-draft (TJ4.0) and up-draft stoves with chimney were tested according to 6 hours testing protocol which is used for the Hebei Clean Air Project. This protocol consists the ignition phase for 45 min, low power banking fire stage for 4 hours, high power cooking and heating stage for 45 min and high power heating for 45 min respectively. There are two types of stove used for determining the efficiency and emissions in cross-draft and up-draft combustors. These stoves are operated same manner as a top-lit up-draft ignition method. Combustion process of TLUD takes place in different stages. Such as, the fuel is dried initially as fuel moisture driven off by high temperature. After burning fuel is dried, the pyrolysis stage formed as the volatile matter is driven off from the solid fuels (Makonese, 2015). However, there are differences of combustion process in the combustion chamber for each stove.

Difference for air flow is presented in following Figure 2-2. The stove design is not only technical issue and but also human health issue. It needs to be easy to use, safe, efficient and non-polluting when people use it for their energy needs. Stoves that use less fuel and emit less smoke are the result of the efforts of hundreds of people who have developed solutions over the years (Maccarty, 2011).



a. Air flow for cross-draft stove b. Air flow for top-lit up-draft stove

Figure 2-6: Difference between the cross-draft and up-draft stoves

2.1.1.1 Cross-draft stove

The cross-draft type of stove is operated in the same manner as a top-lit updraft (TLUD) stove, in that all gases have to pass through hot bed of coke to reach the gas combustion region. The up-draft type allows vertical upward flow, while in a cross-draft stove, airflow is ducted horizontally through the coke bed. The cross-draft architecture can be refuelled while in operation, without risking a burst of high PM emissions, whereas the TLUD is a 'batch' process which generates large quantities of PM emissions if refuelled from above. The air enters the grate on upper side and proceeds down and under the lower brick and burns coal pyrolysis sideways and the gases burn upwards through the constriction of the two bricks. Emissions and flames flow into a pipe engaged at the back of the combustion chamber. The fire is lighted next to this channel and hence all smoke generated from the ignition of solid fuel would be mixed with flames and burn inside of pipe. Therefore, it results PM emissions emitted lower during the combustion (Pemberton-Pigott, 2016).

2.1.1.2 Up-draft stove

In the top-lit up-draft (TLUD) design, the solid fuel is supported into the combustion chamber and ignited from the top. The primary air flows into the bottom of the stove up through the grate and flows upward through the fuel stack. It results in partial oxidation of the fuel into CO, H_2, hydrocarbons, CO_2, and H_2O, in the primary combustion zone. After the hydrocarbon gases are driven off what remains is called char, sometimes known as charcoal and which comprises almost exclusively carbon (Andreatta, 2007). The hot char above the primary combustion zone reduces some of the CO_2 and H_2O produced in the primary combustion zone back to CO and H_2. A secondary air source which is preheated by the wall of the combustion chamber is mixed with the combustible gases leaving the char zone to form the secondary combustion zone. When the combustible gases mix with the secondary air the combustion is completed. It usually happens in a very turbulent hot flame (Tryner et al., 2013). It shows in Figure 2-3.

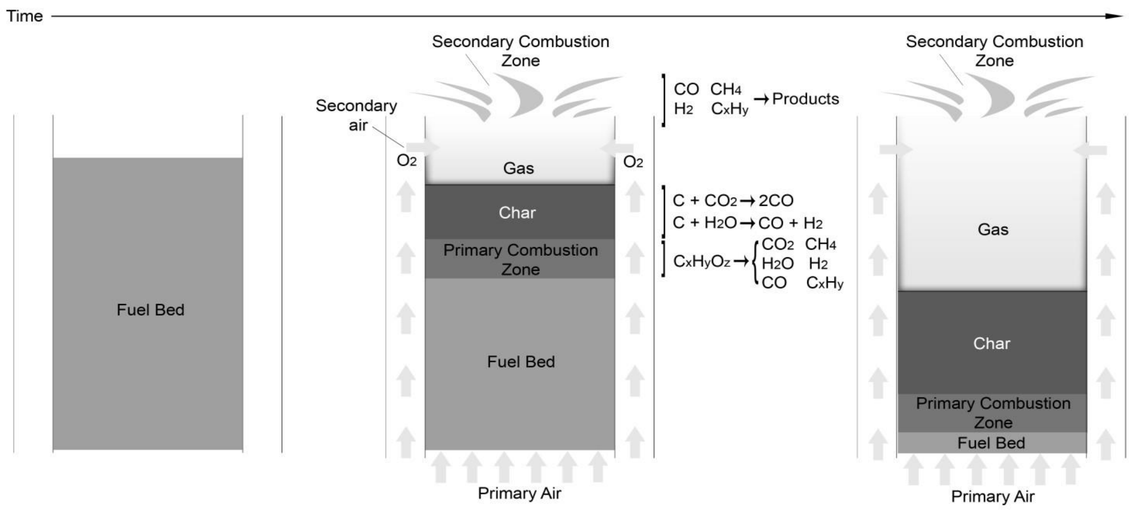


Figure 2-7: Schematic of top-lit up-draft stove (Tryner et al., 2013).

The advantages of this type of stoves are its simplicity and internal heat exchange leading to low gas exit temperatures and high efficiencies. Because of the internal heat exchange the fuel is dried in top of the combustion chamber and therefore, fuels with a high moisture content can be used. Major disadvantages are created the high amounts of tar and pyrolysis products, because the pyrolysis gas is not combusted (Kythavone, 2006). Combustion conditions have great influence on the fine particle and gas emissions which are mainly composed of organic matter, elemental carbon and fine ash because of incomplete combustion. There is a possible way to decrease particle and gas emissions by developing combustion appliance itself (Tissari, 2008).

2.2 Testing Method

2.2.1 Heterogeneous Stove Testing Protocols for emissions and thermal performance

The experimental procedure is described for thermal efficiency, particle and gaseous emissions performance, fire-power and fuel burn rate according to the Heterogeneous Stove Testing Protocols (HTP) which is developed by the Sustainable Energy Technology and Research Centre (SeTAR), the University of Johannesburg for a range of stoves and fuels. The protocol requires each appliance to perform realistic tasks (boiling water in two litre and six litre pots) at three different power levels and it includes the *SeTAR data calculation sheet*, a tool used to capture the raw data from gas analysers, PM monitors, and temperature loggers. The raw data is captured at 10 second intervals during whole testing sequence. Raw data from the flue gas analysers for ppm *(v)*, while the raw data from the PM monitors for mg/m^3, the fuel and system mass for grams, and temperatures for °C are given respectively.

The calculation of emission factors is critical to considering the comparison of stove performance for different stove fuel combination and is given to gas concentration that is normalized for dilution by excess air. Although, if each stoves are diluted by different amount of air it cannot be compared gas emissions from two stoves. Excess air is the measurement of air in the gas which is not used during the combustion and it is important factor for the stove design and operation to optimize for low pollution emissions. Lambda represented by λ is expressed the total air demand that is used during combustion process plus the air not used. Total amount of emissions from the combustion is affected by the amount of diluted air in the sample. Total air demand is calculated as follow:

$$\lambda = 1 + \frac{O_{2meas} - O_{2oxid}}{O_{2det} - (O_{2meas} - O_{2oxid})} \qquad \text{(Eq. 2-1)}$$

Where, O_{2meas} is the measured oxygen, O_{2oxid} is the oxygen required to complete combustion, O_{2det} is the total oxygen in all detected gases.

The HTP uses the carbon mass balance method which uses a sample of the emissions and mass of fuel burned to indicate the total mass of all emissions. The mass of $PM_{2.5}$ is multiplied by dilution in the equipment and then multiplied by λ to get total mass of emissions. This method is to determine the performance in the real time while the fuel is burning in inhomogeneous. Metrics for the particle mass concentration are the mass of PM emitted per $\text{MegaJoule}_{\text{NET}}$ of energy delivered into the pot or the mass of PM $\text{MegaJoule}_{\text{NET}}$ of energy delivered from the fire.

The ash is remained on the mass balance when calculating the heat from the fuel burned. When 1 kg of fuel is burned, the change in mass is not 1 kg, however, 1 kg factored for the mass of ash in the fuel. Fuel moisture which reduces the net heating value in the fuel must be measured. The heat released per kg of mass disappearing from the scale is higher than the heat value As Received (AS) per kg because the ash is presented. It is necessary to calculate the heat transferred to the pot and released from how much fuel. The heat contained in the charcoal remaining that is not burned in the stove is crucial for determining the heat transfer efficiency. Heat value of the charcoal is subtracted from heat value of the fuel ignited.

Ash remained in the charcoal at the end of the test must be considered because it affects to the heat released. If the ash is not subtracted from the total mass there will be created an error. Without determining the heating value of the char, the amount of ash as a percent is uncertain. The smaller amount of charcoal remained, the larger error caused by the ash as it constitutes proportionally larger fraction of the total.

2.2.2 Burn sequence

In addition to selecting stoves-fuel combinations for testing, before any testing commences it is necessary to determine a burn sequence, that is, the sequence of operations to be carried out on the stove during the test. This period should start just before ignition and continue until burnout or test end and include intervals periods of high, low or medium power operation and instructions on whether the operator should refuel or otherwise adjust the stove. The choice or design of a burn sequence is a local variable, often referred to as a contextual burn sequence. A contextual burning sequence is informed by the local customs cooking, food preferences, cultural and gender-determined roles of work division, fuel availability and cost, or the agenda of an external agency, government or international funding agency. Because of these variables, it is impossible to define a universal burn sequence that could allow comparison of differing technologies and fuels without compromising the design intent of a stove or fuel combination. Instead, the output metrics of energy efficiency, specific PM and CO emissions (indexed to useful energy) have universal comparability, irrespective of the contextual burn sequence used to derive them.

The burn sequence selected was adapted from the Hebei Clean Air Project six-hour test protocol and is taken as contextually appropriate to the circumstances of rural and semi-rural western China, a region rich in coal resources and with moderate to severe winter climate. The derivation of the test is an assumption that a farming family will ignite the stove on a daily basis. The sequence consists of a series of high and low power operations, including one cooking simulation. The test is divided into four phases: (i) An ignition and rated heating power phase; (ii) An extended low power phase; (iii) A combined cooking and heating phase; and (iv) A high power heating only phase (Figure 2-4). However, when evaluating the performance of a device for a whole season (during which a stove will be kept burning more or less continuously for an entire season), ignition phase and its associated emissions may be ignored and excluded from the calculations of the output metrics.

This test sequence is intended for use when rating the performance of space heating stoves that also cook. In addition to the cooking and space heating functions, all heating stoves must be able to heat water in three vessels simultaneously.

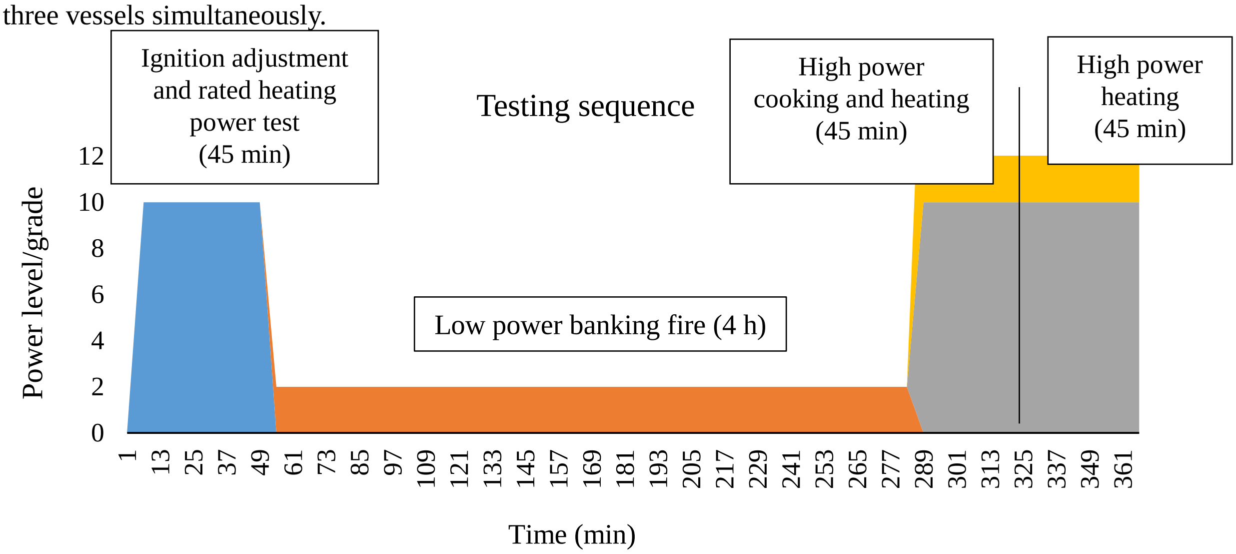


Figure 2-8: The Hebei Clean Air Project six-hour test sequence (BST laboratory of CAU, Beijing, China)

Ignition phase for 45min

Ignite the stove and operate according to the Technical Test Sequence. Set the thermocouples if they are necessary. Adjust the air controls until the combustion reaches to the stable condition at high power. If the ignition phase is to be included in the emission test, this condition is allowed to continue for 45 min. Note the starting and ending times of this first phase. If the ignition phase emissions are to be ignored (seasonal test) proceed to phase two immediately without waiting for the full 45 min.

Low power heating phase for 4 h

Fuel the stove with a mass of fuel determined either from field observations of ‘overnight refueling mass’ or the manufacturer’s recommended maximum fuel load. Immediately after loading the fuel, adjust the air inlet to low power setting for four hours without further adjustment of the controls. Note the ending time.

High power cooking and heating phase for 45 min

In this sequence, it uses the heat released during burn series for cooking. This stage starts with the placement of the cooking vessel on the stove and ends when the vessel is removed. Select the cooking vessel larger in diameter than the biggest opening of the cooking station. The cooking pot is fitted with heat exchanger to permit the continuous removal of heat such that the temperature of the water in the vessel never exceeds 70℃ during the test. Determine the initial mass of water in the pot and record the starting temperature of the pot water. Refuel the stove and note the mass of the added fuel. Adjust the stove to high power and then place the pot onto the cooking station. Note the starting time of the cooking phase (the heating test will not stop). Record the total mass of the water passing through the pot heat exchanger during the cooking phase and the average water temperatures at the inlet and outlet of the pot heat exchanger. After 45 min have elapsed, remove the pot position. Record the time of pot removal and the remaining end mass of water in the pot. Calculate the heat gained by the cooking vessel and the average rate of heat gain (W).

High power heating phase for 45 min

The high power heating phase is continuous with the previous cooking phase. Allow the stove to continue operating at high power, without further adjustment or refueling, for a further 45 min.

The test is ended either after 45 min or earlier if the fire in the combustion chamber burns out. According to the selected requirements for the test, excluding the ignition period and determine the total mass of $PM_{2.5}$ and CO emissions (mg), (g) and divide by the total MegaJoules of energy delivered into the heated space or cooking pot. Report the resulting metrics in the form $PM_{2.5}/MJ_{Delivered}$ and $CO/MJ_{Delivered}$.

Based on the people behavior on the stove operation in their home, the experiments were conducted. For example, Figure 2-5 shows that the hourly measurements of PM for daily variations that correlate with the daily routine firing practices of the typical ger stove in Mongolia. PM hourly concentrations on

November 19-20 at the Takhilt meteorological site in a Ger area to the west of Ulaanbaatar city center (Ede, 2011). Clear peaks are shown in the morning (the right-most peak in the figure) and two-three successive peaks in the afternoon/evening. It is associated with ger stove firing periods. The evening peak is longer, corresponding to prolonged firing, while the morning firing is shorter, for heating and cooking before going to work. The evening peaks correspond to stove loadings (Ede, 2011).

It is might be that in the winter time when people keep the stoves cold, they ignite the fire in the stove for twice or more times in a day. This makes much more pollution than the stoves are kept hotter for whole day. By an approximate calculation, about 50 percent of PM concentrations relates to the morning ignition phase (cold start) (8:30-9:30), the evening phase (18:30-19:30), and during the reloading of stoves (20:30-21:30).

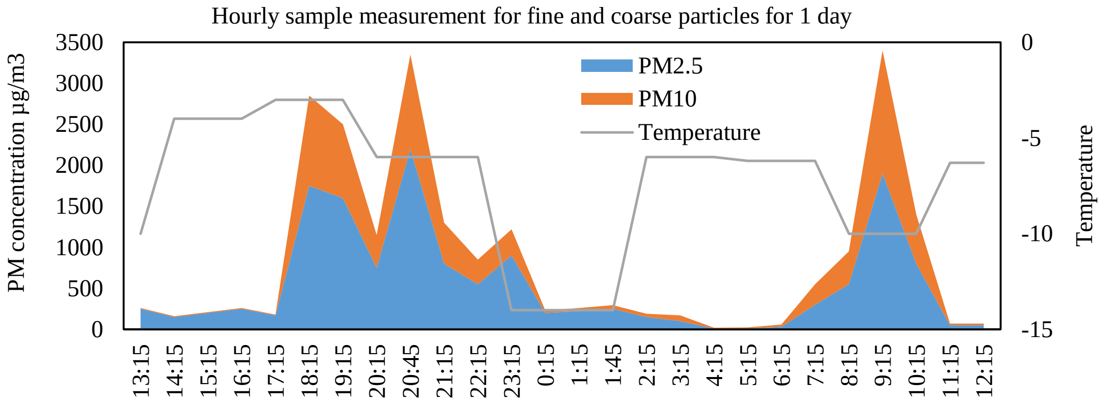


Figure 2-9: Example of time series of PM for one day at the beginning of winter at Takhilt meteorological site in Ulaanbaatar city, Mongolia

2.2.3 Testing procedures

The process of a typical stove test for energy and emission metrics is outlined in this section. Detailed checklists for the operation of a test are provided in Appendix A: A1. Preparation for a test up to the point of ignition; A2. Monitoring a test and A3. Ending a test.

- Select stoves and fuels.
- Plan the fuel/stove combinations to be tested and the number of replicate measurements.
- Determine the burn sequence to be used for the set of tests.
- Procure and prepare an adequate quantity of fuel and firewood for kindling for the planned number of replicate tests. This stage includes crushing and screening to obtain desired size range of fuel pieces.
- Send a coal sample for chemical and physical analysis.
- Review safety precautions and availability of safety equipment in the laboratory.

- Install the stove on the test rig and conduct checks and preparations as per Appendix A1. Specifically, ensure that the chimney is attached so as to avoid touching the roof or other structure.
- Prepare 200 to 500 g of firewood, broken into thin pieces to use as kindling and a similar amount of small coal pieces.
- Weigh the amounts of kindling and fuel for the entire test and place the fuel in containers on the mass balance on which the test stove is located. The fuel containers and any unused fuel of kindling should remain on the balance for the duration of the test.
- Switch on all electronic apparatus and data loggers, check and zero as required. Switch on all gas flows.
- Lay the kindling in the stove.
- Start the data loggers. Record the starting and ending times of each phase and any other operation on the stove during the burn sequence in the laboratory notebook.
- Ignite the stove following the procedure described above. Once the flame is established, closed the cooking hole with the cover.
- After the initial coal load has ignited, load the fuel hopper with the planned quantity of coal.
- Follow the selected test sequence for the six-hour test and the checklist A2. Monitoring a test. Record all operations and any deviations in the laboratory log book.
- Complete the test by following the checklist A3 Completing a test.
- Download and backup data. Enter data file names into the laboratory logbook.

Process the data and calculate the output metrics.

Chapter 3 Thermal performance of TJ4.0 under different stove-fuel combinations

This chapter presents details of the description for stoves and characteristics for all types of fuel tested in this study. Equations defining the energy are given. In addition, the results of energy efficiency of the two stove designs and different types of fuel with different size ranges are presented and this chapter ends with brief summary of comparison of the efficiency of these stoves.

3.1 Introduction

Thermal efficiency is the ratio of work done by heating and evaporating water, to the energy generated. Moreover, it is expressed by the heat of fuel losses from the gases going up the stack. Stack loss is carried away by dry flue gases and the moisture loss in the stack. The stack temperature reflects the energy do not transfer from fuel to the heat exchanger and therefore, the less stack temperature, the more efficiency heating appliance. The combustion efficiency includes losses from dry gas, moisture and the CO production.

Energy efficiency is determined by dividing the heat output of an appliance by the energy content of fuel supplied to the stove. Every fuel has specific heat content. Heat exchanger is ability to transfer heat to the room and determined how well the heat created by the combustion process has been taken places. Depending on type of appliance, a certain amount of heat flow out of the flue to prevent gasses from condensing which is needed because of additional heat extracted the flue gases. This is the latent or hidden heat. The exact airflow and the air temperature should be measured in or order to calculate energy efficiency of the appliance. Stack temperature is to provide the heat in the flue to prevent water formation which can be liquid product of the combustion from condensing in the flue or chimney.

Once the fuel has combusted, the heat is transferred to the heat exchanger or directly to the air. There are some losses to the appliance by radiation and conduction. Radiation is the heat transfer between surfaces at different temperature without any physical contact. Conduction heat transfer caused by the increased activity of molecules within a body and depends on molecular structure of the material. It heats completely an object once the object has been heated by radiation and conviction. Convection is the heat transfer from the flue gas to the heat exchanger by hot gas to cold object. The more turbulent the flow, the greater the heat transfer by convection. The heat must penetrate numerous layers of air to transfer energy to the heat exchanger. It is more efficient through the development of more complex heat exchanger designs and better burners (James, 2006).

3.2 Materials and Methods

The experiments described in this thesis were conducted using two stove types: a novel pre-production design cross-draft coal gasifier, designated TJ4.0 and a conventional, widely used coal burning Chinese top-lit updraft space heating stove, which was selected as a baseline reference device against which to evaluate potential improvements in efficiency and emissions. Each stove type was tested for two different fuels: (a) raw coal, in two size ranges, 16-25 mm and 25-40 mm and (b) semi-coked coal briquettes (size 16-25 mm). (See Chapter 1, Figure 1-4). The experiments were performed under laboratory conditions in the Biomass Stove Test Laboratory (BST) of China Agricultural University, Beijing. The laboratory aims to provide scientifically reliable fundamentals for the testing protocols and promote the development of biomass stove industry as well as reducing the greenhouse gas emissions. Determinations were made for fuel-stove combinations of the energy efficiency, the fuel consumption rate, CO and PM mass per delivered MegaJoule. The burn sequence and the data processing procedures are described in the following sections. Four or five repeat tests were conducted for each stove-fuel combination.

3.2.1 Stove Description

The TJ4.0 design was selected as a cross-draft combustor. The structure of the stove is shown Figure 3-1.

Figure 3-10: Design of the TJ4.0 cross-draft stove (120 m^2)

The order of laying fire is to fill the hopper partially, then place one layer of small coal pieces on the grid, followed by small pieces of firewood and again a small amount of coal. 200 to 300 g of firewood were used and then the fire is ignited through the cooking hole, using an ignited piece of kindling wood to reach to the bottom of the combustion chamber. The fuel hopper is filled at an appropriate time after the fire has been established. In this experiments, for the cross-draft stove, 8 - 11 kg of fuel were added for one complete test for each fuel according to the 6-hour testing sequence (Figure 4-4). For larger size coal lumps and semi-coked coal briquettes, the grate was first loaded with a layer of small sized pieces to create conditions for rapid ignition.

The fire is ignited through the opening of the cooking station above the combustion chamber. Initial combustion gases from the kindling (low flow) can flow through the bleed hole (Figure 3-1) in the baffle plate, allowing a draft to be initiated even while the stove is still at a low temperature. Air enters the grate through the air door and proceeds down and sideways through the fuel bed, passing under the lowest brick (the bridge) separating the fuel hopper from the combustion chamber. The air and pyrolysis emissions then move upwards into the combustion chamber where the gases combust. From the combustion chamber, hot gases and emissions flow against the bottom of the cooking station into the heat exchanger. Once the fire is fully established, the high volume of hot gases causes most of the air entering the heat exchanger to move downwards under the baffle plate and then upwards to the chimney outlet. The pyrolysis front in the coke layer moves sideways towards the air door, pyrolysing new fuel as it moves gradually down from the hopper. As a result of the pyrolysis gases being forced to flow through the coke bed, complex semi-volatile molecules are reduced to simple gases that can be fully combusted in the combustion chamber and hence PM and CO emissions are much reduced.

A typical Chinese household space heating and cooking up-draft stove was tested for thermal performance, emissions and particles. Tests were conducted under laboratory conditions (Figure 3-2). The stove can be used on both raw coal and briquette.

Figure 3-11: Chinese typical space heating and cooking stove as an up-draft (100 m^2)

The stove is run same as top-lit up-draft ignition method which the fuel is fed and ignited from top, primary air is blown through the fuel bed. The hot air blown above the fuel bed, drives off the volatile components from the burning fuel and then emitted volatile components are thoroughly mixed with air before combustion process has been taken place. It has a side door for secondary air which is recommended to use when low power for both raw coal and briquette and high power for raw coal. The ash door should be opened for high power and closed for low power. When refueling on hot burning surface of the stove from top, the emissions is highly produced to compare with the cross-draft.

3.2.2 Characteristics of Fuels

Different types of fuels which are commonly used for space-heating stove for cooking and heating in China were selected for this experimental investigation. These fuels are: small raw coal (16-25 mm size), large raw coal (25-40 mm size), and semi-coked coal briquette (16-25 mm size) in the cross-draft stove and raw coal (unsorted) and semi-coked coal (60 mm) in the up-draft stove. These characteristics have largely effect on the outcome. The specifications of the fuels were obtained from the previous tests and sample of the fuels was sent to laboratory to determine technical parameters and elemental structure. The characteristics of the fuels selected are given in Table 3-1.

Table 3-3: Characteristics of fuel that used

	Technical analysis				Ultimate analysis				
Samples	Moisture %	Ash %	Volatiles %	Heating Value, (Q) MJ/kg	C %	H %	N %	S %	O %
Raw coal	9.0	5.7	27.1	28.02	72.0	4.84	0.99	0.39	21.7
Semi-coked coal briquette	3.5	15.7	10.2	25.92	74.1	1.46	0.99	0.41	23.0

*C, H, N, S and O – carbon, hydrogen, nitrogen, sulphur and oxygen respectively.

3.2.3 Formulas for Energy Efficiency

Energy efficiency for heating is defined as by the amount of heat a stove generates and transfers to the room during a test sequence, relative to the energy content the fuel loaded into the stove and the difference between ambient air and flue gas temperatures respectively. For combined cooking and heating stove, some of the heat is transferred to the pot while some to the room. For the cooking performance, in which water is used as the working fluid in the pot, the useful energy includes both the sensible heat gained by the water and the latent energy of vaporization of any evaporated water.

3.2.3.1 Cooking efficiency

Cooking efficiency η_c was calculated according to the protocol that developed by the Key Laboratory of Clean Production and Utilization of Renewable Energy, Ministry of Agriculture. The Protocol has been adopted by the World Bank for Hebei Clean Stove Promotion Project. The efficiency calculation is based on British Standard BS845. The pot is usually placed on the fire well after it is ignited so the pattern is followed in the lab test. It is calculated on the basis of the change in temperature of the pot contents and/or the amount of water boiled out of the pot during the experiment. Total heat delivered into the home includes heat delivered into the pot so cooking heat is a component of the delivered heat value. It is assumed that heat passing through the pot passes into the living space. Cooking efficiency expressed by the ratio of work done by heating and evaporating water, to the energy produced burning fuel and is represented as:

$$\eta_c = \frac{Q_P + Q_{hex} + Q_{wf}}{B_F \times Q_{LHVf} + B_i \times Q_{LHVi}} \times 100\% \qquad \text{(Eq. 3-1)}$$

Where, Q_P is the heat gained by the pot (J), Q_{hex} is the heat gained by the heat exchanger (J), Q_{wf} is the heat gained by the working fluid flow, B_F is the mass of raw fuel burned (kg), B_i is the mass of ignition material (kg), Q_{LHVf} is the lower heating value As Received of the fuel and Q_{LHVi} is the lower heating As Received value of ignition material (MJ/kg).

Cooking efficiency is a function of the heat gained by the pot, the water in the pot, heat exchanger and working fluid flow. It is given by the following formulas:

Heat gained by the pot and water:

$$Q_P = (G_P + G_L + G_{Th}) \times (C_P Pot / 4.186 + G_W) \times (t_f - t_i) \times 4.186 \qquad \text{(Eq. 3-2)}$$

Where,

Q_P = heat gained by the pot (J)

G_P = pot mass (g)

G_L = lid mass (g)

G_{Th} = thermocouple mass in the pot (g)

$C_P Pot$ = specific heat of the pot materials (J·g^{-1} K^{-1})

G_W = water mass in the pot (g)

t_f = final water temperature (℃)

t_i = initial water temperature (℃)

4.186 = specific heat of water (J·g^{-1} K^{-1})

Heat gained by the heat exchanger:

$$Q_{hex} = \left[\left(G_{ex.p} \times C_p Pipe + G_{ex.wf} \times C_P Fluid\right) / 4.186\right] \times \left[\left(t_{hef} - t_{hei}\right) \times 4.186\right] \qquad \text{(Eq. 3-3)}$$

This simplifies to:

$$Q_{hex} = \left(G_{ex.p} \times C_p Pipe + G_{ex.wf} \times C_P Fluid\right) \times \left(t_{hef} - t_{hei}\right) \qquad \text{(Eq. 3-4)}$$

Where,

Q_{hex} = heat gained by the heat exchanger (J)

$G_{ex.p}$ = heat exchanger pipe mass (g)

$G_{ex.wf}$ = heat exchanger working fluid mass (g)

$C_P Pipe$ = specific heat of heat exchanger pipe (J·g^{-1} K^{-1})

$C_P Fluid$ = specific heat of heat exchanger working fluid (J·g^{-1} K^{-1})

t_{hef} = heat exchanger outlet temperature (℃)

t_{hei} = heat exchanger inlet temperature, (℃)

Heat gained by the working fluid flow is given by:

$$Q_{wf} = G_{wf/s} \times (T_f - T_i) \times C_p Fluid \times (t_{hef} - t_{hei}) \quad \text{(Eq. 3-5)}$$

Where,

Q_{wf} = heat gained by the working fluid flow (J)

$G_{wf/s}$ = working fluid flow rate ($cm^3 \cdot s^{-1}$)

$C_P Fluid$ = specific heat of the fluid, ($J \cdot g^{-1} K^{-1}$)

T_f = final time, (s)

T_i = ignition time, (s)

t_{hef} = final water temperature (℃)

t_{hei} = initial water temperature (℃)

3.2.3.2 Energy efficiency

Energy efficiency η_h was calculated by the CO-compensated Siegert Loss Method as specified in the protocol that developed by the Key Laboratory of Clean Production and Utilization of Renewable Energy, Ministry of Agriculture. This is a counterbalance method which compensated energy losses from hot gases in the chimney. It is calculated based on the determination of total system losses up the chimney (chemical and thermal). Heat delivered is total heat available from the fuel minus losses. The efficiency of the stove is found by subtracting the loss from 100%.

$$\eta_h = 100\% - SL \quad \text{(Eq. 3-6)}$$

The efficiency might be significant in some circumstances including losses due to unburned fuel in ash, radiation and convective losses in the appliance, water vapor concentration of the ambient air.

The stack loss (*SL*) is percentage of heat produced in combustion process which is convicted with the combustion gases and it is calculated as follows:

$$SL = (t_2 - t_1) \times (\frac{A_1}{CO_2} + B) \quad \text{(Eq. 3-7)}$$

Where, t_2 is flue gas temperature in the stack (℃), t_1 is ambient air temperature (℃), CO_2 is the concentration of CO_2 in stack gases by volume (%).

A_1 = Siegert constant for the fuel (British Standard BS 845: Part1: 1987):

$$A_1 = \frac{253 \times [C]}{Q_{gr}} \quad \text{(Eq. 3-8)}$$

Efficiency can be determined by separating the fuel, char and ash by measuring the proportions of each and calculating the energy content of each. Ash content in the fuel burned from the combustion chamber of stove at the end of the test is measured and so that it can be minimized error.

3.3 Results and Discussions

Energy efficiencies was calculated for each fuel type and size range burned using the top-lit up-draft and TJ4.0 cross-draft stoves. The results are shown in Figure 3-3.

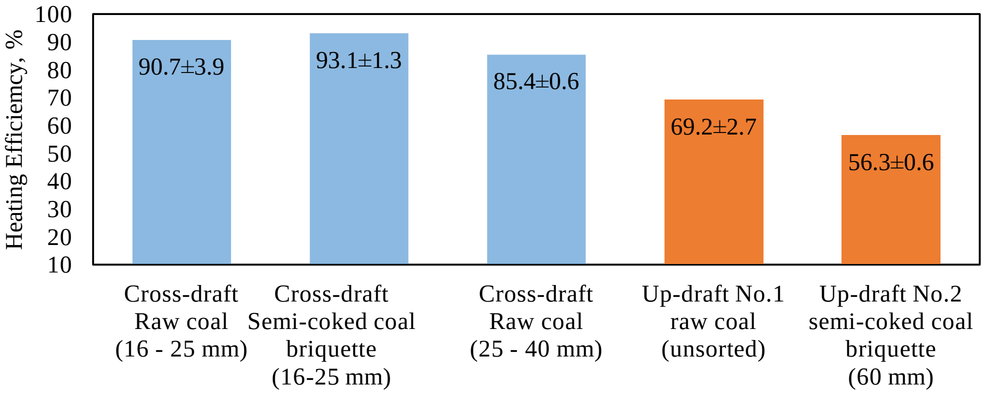


Figure 3-12: Comparison of energy efficiency during burning different type of fuels with different sizes in the cross-draft and up-draft combustors

The large size coal is not as energy efficient the small coal, while the semi-coked coal briquette with size of 16 – 25 mm in the cross-draft stove gave the highest efficiency. The TJ4.0 cross-draft stove was more efficient with all fuels than the up-draft stove.

Although the results were different for each fuel, all met the thermal efficiency requirement of the Chinese Standard NY/T 2370-2013 (minimum heating efficiency is 58%) and the Mongolian National Standard MNS 5216-1: 2011 (minimum heating efficiency is 70%). The up-draft stove did not meet the energy efficiency requirement of the Mongolian National Standard MNS 5216-1 : 2011.

The Figure 3-4 presents that the comparison of the instantaneous fire-power fire-power of the various stove – fuel combinations in the form of time-plots.

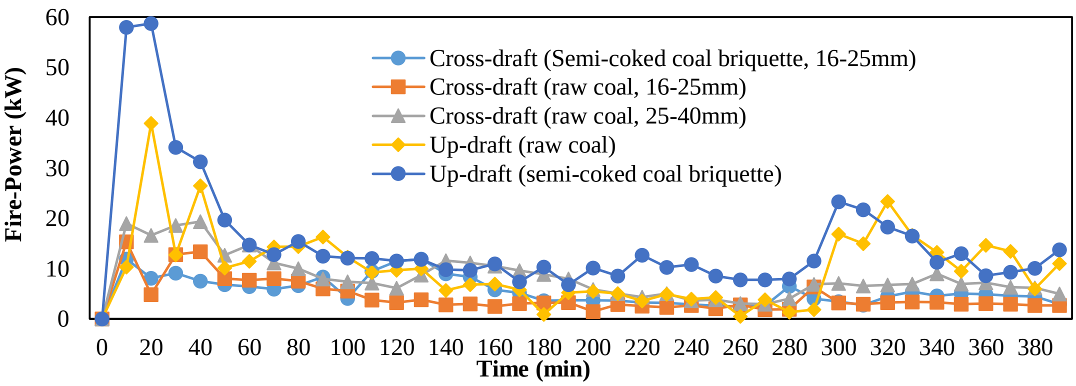


Figure 3-13: Comparison of power (kW) for each stove and fuel combination over the 6-hour testing sequence

Table 3-2 presents the comparison of energy efficiency and fire-power for each stove/fuel combination. Results show that there are not large differences using different fuels on the cross-draft stove. Nevertheless, all type of fuels for cross-draft combustor might be considered to have good efficiency, more than 80% compared with up-draft stove. For fire-power, however, the TJ4.0 stove was lower than the up-draft stove Nevertheless, it still meet the requirement of the Mongolian National Standard which specifies a fire-power between 3 and 7 kW.

Table 3-4: Comparison of average fire-power and heating efficiency over the complete testing sequence when using TJ4.0 cross-draft stove and up-draft space heating stove burning different type of fuels with different size ranges

Stove type	Fuels	Heating efficiency (%)	Difference (A-B)/A (%)	Fire-power kW	Fuel cons kg/h
Cross-draft	A) Raw coal (16-25 mm)	90.7±3.9		3.5±2.4	1.1±0.6
vs. up-draft	B) Raw coal (unsorted)	69.2±2.7	24	6.5±1.6	2.0±0.6
Cross-draft	A) Raw coal (16-25 mm)	90.7±3.9		3.5±2.4	1.1±0.6
vs. up-draft	B) Semi-coked coal brq (60 mm)	56.3±0.6	38	7.0±0.1	2.0±0.3
Cross-draft	A) Raw coal (25-40 mm)	85.4±0.6		6.5±0.8	1.4±0.2
vs. up-draft	B) Semi-coked coal brq (60 mm)	56.3±0.6	34	7.0±0.1	2.0±0.3
Cross-draft	A) Semi-coked coal brq (16-25 mm)	93.1±1.3		4.8±1.13	1.1±0.3
vs. up-draft	B) Semi-coked coal brq (60 mm)	56.3±0.6	40	7.0±0.1	2.0±0.3
Cross-draft	A) Semi-coked coal brq (16-25 mm)	93.1±1.3		4.8±1.13	1.2±0.3
vs. up-draft	B) Raw coal (unsorted)	69.2±2.7	26	6.5±1.6	2.0±0.6

Determined from the experiments, the cross-draft combustor consumed 7-9 kg of fuel from ignition to the end for the 6-hour testing sequence, indicating that it has a lower fuel burn rate compared with the up – draft combustor (about 12 kg). Generally, the up – draft has an average fuel consumption rate of 2-2.5 kg/hr, while the cross - draft combustor has an average fuel consumption rate of 1-1.5 kg/hr. As the results of Table 2-2, the efficiency was very high because the fuel was completely combusted in the combustion chamber. When burning small sized raw coal (16 - 25 mm), the fire power was steady on average 3.5 kW and the efficiency was on average 90.7 %. For semi – coked coal briquette (16 - 25 mm), fire power was on average of 4.8 kW while the heating efficiency was 93.8 %. In case of the bigger size of raw coal (25 - 40 mm), the fire power was 6.5 kW and heating efficiency 85.4 %. There is no substantial difference in efficiency for all fuels when employing the TJ4.0 stove. It shows that the fuel type is not impact to the stove performance. If the combustion condition is right operation there will be complete combustion and lower emissions and high efficiency.

In case of the up-draft combustor burning raw coal, the fire-power was higher on average because there was big fire in the beginning with a falling power level during the low power burn. Although, this drop led to a rise in the excess air level, creating a gradual monotonic increase level of CO. When burning semi-coked coal briquette in the up-draft stove there was large fire in the beginning but the power does not drop as much during the low power burn because the fuel is slower burning due to its density.

Chapter 4 Effect of fuel type and size on $PM_{2.5}$ emissions of TJ4.0 cross-draft stove

This chapter presents the effects of the fuel type and size on $PM_{2.5}$ for the TJ4.0 design as a cross-draft stove. In the first subsection, stove description and fuel characteristics tested in this study are presented. This section is followed by the details of stove testing system of the Biomass Stove Test Laboratory (BST), China Agricultural University. Equations defining the emission factors of PM are given. The layout of the testing system and details of the apparatus are provided. Preparation of the equipment, description of the chosen burn sequence and the testing protocol are described. In addition, the emission performances of the TJ4.0 stove compared with the Chinese up-draft stove which was tested only one unsorted raw coal and semi-coked coal briquettes of slightly larger dimension (60 mm) are given in final part of this chapter.

4.1 Introduction

Many people are exposed to the smoke from incomplete combustion products including carbon monoxide, particulate matter, producing about 20% of global emissions of both organic carbon and elemental carbon (Roden et al., 2008). The particle phase is primarily less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) which is pollutant emission associated with many respiratory diseases (Northcross et al., 2010).

The experiments were conducted using cross-draft (TJ4.0) stove burning small raw coal (16-25 mm), large raw coal (25-40 mm) and semi-coked coal briquette (16-25 mm). Each hour the thermal efficiency, the fuel consumption rate, CO and PM mass per delivered MegaJoule which is the metric for PM per heated to the room and the exhaust gas temperature for each fuel and stove combination were determined. The mg/m^3 metric of PM is a mass concentration, where it's the estimate mass of PM in a cubic meter of air. Emission factors are usually expressed as the mass of the pollutant divided by unit mass, volume, distance or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per mega gram of coal burned). These factors make it possible to estimate emissions from various sources of air pollution (Nussbaumer et al., 2008). Burning one kg of fuel doesn't give the meaning of how effective the stove was at delivering heat to the house. Therefore, it is necessary to determine the PM mass considering the efficiency which means dividing the emissions per MJ of fire by the efficiency of delivering the heat. If the PM created per MJ delivered is lower, the stove is correctly designed to get complete combustion.

Emissions can vary significantly in both qualitatively and quantitatively depending on appliance type, fuel properties and operation (Boman et al., 2005) as well. In most combustion systems, if excess air is insufficient to the combustion process, there will be produced the unburned fuel, soot, smoke and carbon monoxide thereby limiting the combustion reaction. Even if there is high excess air it can lead lower combustion efficiency. Therefore, it needs to provide optimal amount of excess air.

In this study, $PM_{2.5,}$ CO and CO/CO_2 ratio were measured through holes made on chimney for taking flue gas samples. All these measurements were made in each 10 seconds and stored in computer in digital form and then summarized and used for analyses. Results of $PM_{2.5}$ emissions formed from the TJ4.0 cross-draft stove burning small raw coal (unsorted) and semi-coked coal briquette (60 mm) are presented in below.

4.2 Stoves and Fuels

In this study TJ4.0 design as a cross-draft stove and a typical Chinese household space heating and cooking stove as an up-draft stove were selected as a baseline reference technology and tested for $PM_{2.5}$ emissions. The description of the stoves were presented in Figure 3-1 and Figure 3-2, Chapter 3.

Different types of fuel with various size ranges are tested for the cross-draft stove and up-draft stove in this study. These fuels in the TJ4.0 design as a cross-draft stove are: small raw coal (16-25 mm), large raw coal (25-40 mm) and semi-coked coal briquette (16 - 25 mm). For the up-draft stove, the fuels are: raw coal (unsorted) and semi-coked coal briquette (60 mm). Characteristics of this fuels are presented in the Table 3-1, Chapter 3.

4.3 Equipment and Methods

4.3.1 Instrumentation

The all data is collected from three independent systems including temperature, mass and emissions measurements. The instruments for testing are shown in Table 4-1. Temperatures are measured and recorded at the outside, ambient, roofline in the chimney coolant 1 (Pot in), coolant 2 (Pot out). Temperatures associated with the stove are tested with KeySight Data Collector Temperature measurement instrument and as well as ambient and flue gas temperatures.

Data of mass is collected automatically from the stove scale which has a platform placed the whole stove and recorded into a computer file using a digital capture program.

Emissions data is collected from two different machines which measure gases and particles. All gaseous compounds including CO_2, CO, O_2, NO_x and SO_2 emitted from combustion of the fuels are measured by using the “VARIO PLUS” gas analyzer. Gas flows are controlled with X-Stream device. The flue gases are diluted with mixing with air supplied by a compressor. Based on the ratio between CO_2 gas concentrations in the diluted and undiluted gas streams, the dilution amount of the particulate gas stream is calculated. Gas measurements are placed in the stack gases and at the end of the diluter which is used for CO_2 as a reference to calculate the PM dilution tunnel in real time. In the stack gases, the oxygen, carbon-dioxide and carbon-monoxide are measured. The diluter is dry air.

Table 4-5: List of testing devices and equipment

Model	Type of measurement	Range precision
MRU VARIO PLUS Gas Analyzer	O_2±0.2%, SO_2±5%, NO_x±5%, CO_2±2%, CO±2%, CH_4±2%	
DustTrak TSI Model 8533	Particulate matter: PM_{10}, $PM_{2.5}$	0.001-150 mg/m^3
Keysight data collector and temperature measurement	Temperature measurement	
Thermocouple 34972A+34901A	Temperature measurement	
Stove scale FCN-V10	Measuring stove weight	300kg/1g
Fuel scale	Measuring fuel weight	20 kg
Computer: Dell Model; Processor: i5; RAM: 4 G Byte;	Monitor: 24 inch 2 screens; Video card to connect DVI x2 type 2 screens	
Flowmeter TUF-2000P	ml/second	
Diluter, custom built at BEST, CAU workshop	Flue gas sample dilution for particle measurements, manually preset dilution ratio	

Combustion products are drawn from the exhaust duct through an inlet line heated to the exhaust temperature. The combustion products are then turbulently mixed with dry compressed air. The flow rate of both the dilution air into the tunnel and the combustion products through the inlet line are directly measured. At the end of the dilution tunnel, measurement ports draw the dilution mixture to a gas analyzer (VARIO PLUS flue gas analyser, which measures CO_2, CO, NO_x, CH_4, SO_2 and O_2), a particle analyzer (TSI DustTrak DRX model 8533, which measure particle mass in the range PM_1, $PM_{2.5}$, PM_4 and PM_{10}). All parts of the sampler in contact with the exhaust sample and the diluted mixture are made of stainless steel and Teflon tubes to minimize contamination.

The samplers are equipped with conventional heated sampling stainless steel probes for the stack equipped with thermocouples to measure stack gas temperature. The stack exhaust passes through a *venturi* constriction into the mixing tunnel Figure 4-1. The mixing tunnel was designed to fully mix the undiluted stack gas and dilution air with minimal back mixing and with low pressure drop. The SeTAR Centre design also avoids high concentrations of exhaust gas sample along the walls to minimize wall losses and presents a relatively uniform velocity profile to the outlet ports where the stack gas is channelled to gas and particulate analysers for real-time monitoring.

After dilution of the flue gas extracted from the chimney, the particulate content is measured by a "TSI DustTrak" particle analyzer. Particle mass concentrations and size separated mass fraction concentrations were monitored by using a DustTrak TSI 8533 aerosol monitor. The instrument simultaneously measures size separated mass fraction concentrations (PM_1, $PM_{2.5}$, PM_4, PM_{10} and Total Suspended Particulate-TSP) over concentration range 0.001 – 150 mg/m^3 in real time. When the instrument is operated, the aerosol particles are constantly recorded into the sensing chamber using a diaphragm pump and it is flown through a HEPA filter. The remaining flow (sample flow) passes directly through the inlet into the sensing chamber where it is illuminated by a sheet of class 1 laser light formed from a laser diode. The emitted laser beam initially passes through a collimating lens, and a cylindrical lens to create a thin sheet of light. The sampled aerosol particles will then scatter this light, upon which a significant fraction is captured on a gold coated spherical mirror before it is focused onto a photo-detector. Figure 4-2 shows a schematic of the aerosol measurement, signal acquisition, and signal processing which occurs in a DustTrak monitor. Because of a less sensitive photometric signal to large particles, the DustTrak TSI aerosol monitor is able to measure mass concentrations with relatively greater accuracy; it is able to accurately measure single particles >1µm. The unit can also be calibrated using gravimetric samples which entail the side-to-side monitoring of the monitor readings and gravimetric samples to determine the accuracy of mass measurements. For gravimetric analysis, a 37 mm filter cassette sampler is inserted in-line with the aerosol stream at the outlet of the optics chamber allowing for gravimetric analysis without the need of an external pump and filter holder.

Before the test, the instrument for PM needs to perform zero calibration and also there is need to measure the ambient PM level in the laboratory air. This air affects the total measured in the stack because it is already contaminated.

4.3.2 Equipment layout

A schematic layout of the stove test apparatus at the BST Laboratory is shown in Figure 4-1. The equipment comprises several subsystems: an electronic mass balance on which the combustor and all fuels to be used in a test sequence are placed, a set of thermocouples for recording temperatures, a gas sampling stream for extracting and analysing particulate concentrations, and electronic data logging systems.

All measuring devices and equipment calibrated as scheduled and checked before each test. In preparation for testing, the stove to be evaluated is placed on the mass balance. The chimney is installed so as not to have any contact with the roof of the building. The flue gas sampling ports and a flue gas dilution device are installed as shown in Figure 4-1. A separate smaller electronic mass balance is used to pre-weigh the firewood and small coal to be used for ignition and kindling and the main fuel load.

The following parameters are measured every ten seconds during a test according to the protocol. Mass on the electronic balance (stove plus fuel loads), temperatures and emissions of CO, CO_2, O_2 and PM in the flue gas. The temperatures measured include the outside and indoor air temperatures, the temperature of the flame, stove top cover, flue gas duct, chimney inlet and the place where chimney exits the roof. All data are recorded on a computer data logger. Post processing of the results is carried out by importing the logged data into an automated Excel spreadsheet (version number: SeTAR analysis sheet v.3.07). Depending on whether the stove is re-ignited on a daily basis or is intended to burn continuously for many weeks, the calculations of output metrics are adjusted to include or exclude emissions during the ignition phase of the burn sequence (see below).

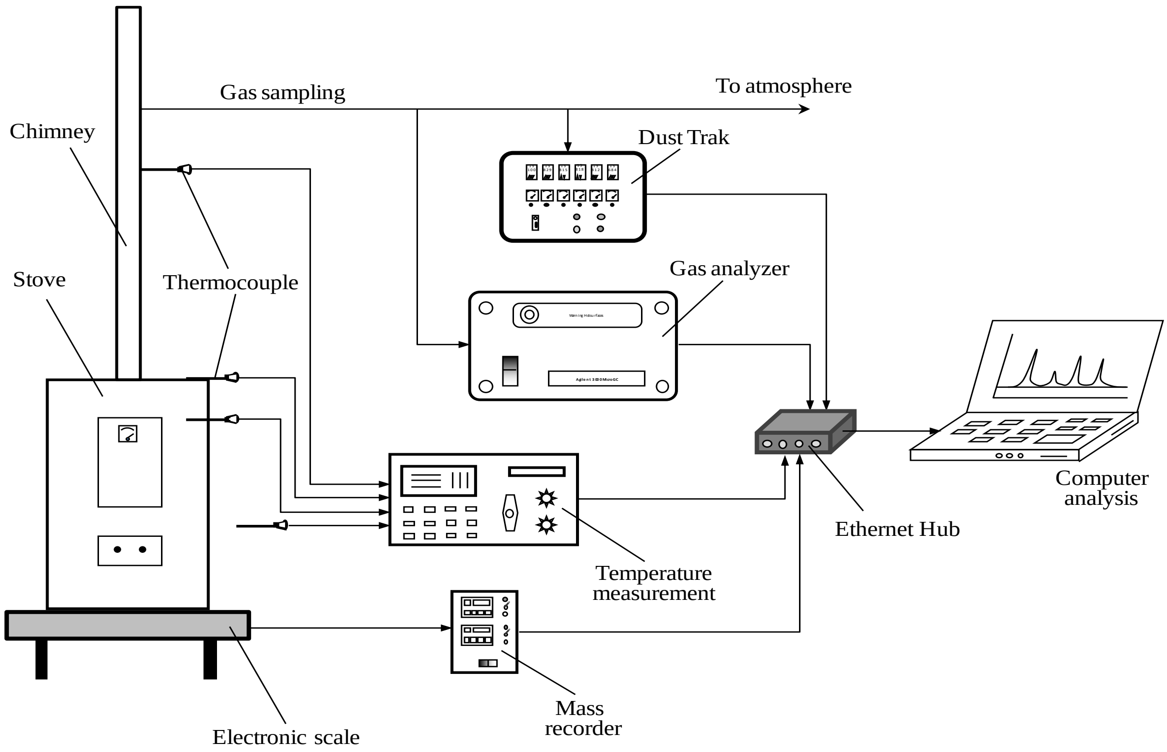


Figure 4-14: Schematic illustration of the stove testing experimental set-up at BST Laboratory, CAU

4.4 PM specific emission factors

When the kindling material ignited, the fuel immediately began to emit sulphurous odours and dense yellowish smoke which is a consequence of devolatilized organic matter had no reached combustion temperature or had inadequate oxygen to fully oxides. After certain minutes elapsed, the lowest lump of fuel could be ignited for glowing visibly red. Thick white smoke continued for up to 30 min as volatiles were changed gradually from the fuel above rising combustion.

Data is collected into 4 raw data files such as mass, gas, temperature, particle and experiment data respectively and a hand written record of relevant information. Mass data includes the date and time stamp plus the recorded mass. It is recorded automatically to the computer disk using the Digital Scale Capture (DSC) program. The file is written every time a data point is created. Temperature data includes the time a date stamp, the channel number and the recorded values for each. The data is stored automatically. Particle data is stored in the internal memory of the DustTrak DRX. It is retrieved after has stopped using the TSI PrakPro programme. It has to be manually downloaded then manually saved to disk.

The DustTrak DRX is a portable instrument which can be used off-site. Experiment data such as the ambient conditions, the stove description, fuel specification, fuel loading and many other things are stored in a spreadsheet. This information is collected during the test and written on the blackboard which is photographed and stored in the relevant test folder. There is no Auto-saved folder for these files. Each one is created from a Sample and saved together with the test data files. It has a version number at the end, before the file type extension. The spreadsheet is updated from time to time. If accuracy is required for stove comparisons the older files may need to be updated by pasting the data and test information into a copy of the newer version of the spreadsheet.

The calculation for particulate emissions is related to the amount of heat the product delivers into the home. Emission factors for point sources are usually expressed as the mass of the pollutant emitted per unit time (g s^{-1}). These factors make it possible to estimate ambient or indoor concentrations (μg/m^3) from various sources of air pollution using dispersion models (Nussbaumer et al., 2008). Metrics appropriate for reporting the emissions performance of a stove is the specific emission factor, defined by dividing the mass of emissions by the mass or energy content of fuel consumed (supplied to the combustor) over some time interval, or in the case of stoves, over a defined burn sequence. However, burning a quantity of fuel does not give an indication of how efficient the stove is at delivering heat to a house or preparing a meal. Therefore, it is necessary to determine a specific emission factor by dividing the emissions per MJ by the efficiency of delivering the heat. For this work, the metrics for emissions are chosen as the specific emission factors, referenced to the useful heat delivered, for particulate matter and carbon monoxide respectively. As people will heat their homes until they feel comfortable, there are two elements of the calculation that must be integrated to arrive at a meaningful rating number that will allow for comparison between different products operating at different efficiencies and emissions per mass of fuel burned. Equation defining the specific emission factors are presented below.

Specific emission factor for PM (cooking):

$$E_{PM}^{C} = m_{PM} / (Q_P \times \eta_C) \quad \text{(Eq. 4-1)}$$

Where,

E_{PM}^{C} = specific emission factor for PM, referenced to useful heat delivered to pot (mg/MJ)

m_{PM} = mass of pollutant emitted over complete burn sequence, as defined for PM (mg)

Q_P = heat delivered to the pot (J) (Eq. 2-2)

η_c = cooking efficiency (%) (Eq. 2-1)

Specific emission factor for PM (heating):

$$E_{PM}^{h} = m_{PM} / (Q_R \times \eta_h) \quad \text{(Eq. 4-2)}$$

Where,

E_{PM}^{h} = specific emission factor for PM, referenced to useful heat delivered to room (mg/MJ)

m_{PM} = mass of pollutant emitted over complete burn sequence, as defined for PM (mg)

Q_R = heat content of fuel and kindling = $(B_F \times Q_{LHVf} + B_i \times Q_{LHVi})$ (MJ)

η_h = heating efficiency (%) (Equation 2-6)

The particulate matter emissions is calculated as follows:

(1) Mass of PM emitted per m^3 of stack gas is expressed by dilution level and PM mass per diluted m^3

(2) Volume of stack gases is expressed by stoichiometric air demand, mass burned and excess air level

(3) Mass of PM emitted is expressed by volume of stack gases and PM mass per m^3

(4) Heat produced is expressed by fuel mass burned and heat content of fuel per kg

(5) Heat lost (thermal and chemical) is expressed by EA in chimney, Chimney temperature and CO level

(6) Heat gained is expressed by heat produced and heat lost

(7) Thermal efficiency is expressed by heat gained and heat produced

(8) PM per Net MegaJoule is expressed by mass of PM emitted and thermal efficiency

The specific emission factors are general metrics that can be used to compare stove performance across stove technologies, fuel types and contextual cooking behaviors (burn sequence). The choice of stoves, fuels and burn sequences are local variables that are selected in context for specific regions, programs, communities or proposed stove intervention. If the specific emission factors are lower (relative to an appropriate baseline), then the candidate stove may correctly be designed as a clean stove. However, the evaluation of stoves against some specific level of performance, or tiers of performance, is a regulatory, marketing or financial decision and as such will not be discussed in this thesis.

4.5 Results and Discussions

4.5.1 $PM_{2.5}$ emission factors in cross-draft stove

The emission factors are based on whole testing sequence, from ignition phase to four hours low power elapsed and then refuelling after that the fuel burnout. The effects on $PM_{2.5}$ emission when employing the cross-draft stove burning various fuels with different sizes, small coal (16-25 mm), large coal (25-40 mm) and semi-coked coal briquette (16-25 mm) were determined. Results of the average $PM_{2.5}$ emission factors over the testing sequence of each fuel in the cross-draft stove are presented in Table 4-2.

Table 4-6: Comparison of average $PM_{2.5}$ emissions for three fuels in the cross-draft stove

Fuels	Stove type	$PM_{2.5}$ (mg/MJ)	Relative difference (A-B)/A (%)
A) Raw coal (16-25) mm vs. B) Raw coal (25-40) mm	Cross-draft	0.11 ± 0.03 0.20 ± 0.42	45
A) Semi-coked coal briquette (16-25) mm vs. A) Raw coal (16-25) mm	Cross-draft	0.03 ± 0.04 0.11 ± 0.03	73
A) Semi-coked coal briquette (16-25) mm vs. B) Raw coal (25-40) mm	Cross-draft	0.03 ± 0.04 0.20 ± 0.42	85

These results show that the smaller size raw coal $PM_{2.5}$ emissions are significantly lower (45% reduction) compared to the larger raw coal ($P<0.05$). In case of the semi-coked coal briquette, $PM_{2.5}$ emissions was decreased by 73% and 85% relative to the small and large raw coal respectively (Table 4-2). PM can be dependent on the volatility of the fuels. The volatiles react with primary and secondary air, once they have been released. Fuels with high volatility matter can produce higher PM, especially if the combustion does not go to completion and the volatile matter condenses as it is released to the cooler atmosphere (Makonese, 2014).

Time series plots of $PM_{2.5}$ concentrations are presented in Figure 4-2 for three types of fuel in the TJ4.0 cross-draft stove. All fuels generate high peaks of emissions at the beginning of the fire as the ignition materials burn and ignite the primary fuels. The small raw coal (16-25 mm) produced the highest initial emissions. In contrast, the semi-coke the $PM_{2.5}$ concentration drops sharply after the fire is stablished and the fuel bed reaches the pyrolysis phase (30 to 50 min for the coal fuels). For each fuels in this stove, similar levels of $PM_{2.5}$ were recorded during the entire subsequent testing sequence, despite the difference of the emissions in earlier ignition of the main fuel bed. The TJ4.0 stove is concluded that once coal is coked there are no significant differences in emissions between different types of fuel or with different sizes.

As the results of the Figure 4-2, in case of the TJ4.0 stove, the $PM_{2.5}$ emission was unexpectedly low. It is often assumed that coal fuel is inherently smoky, yet these tests showed this was not the case. Igniting the kindling wood during the ignition phase generated high $PM_{2.5}$ emissions time compared with the pyrolysis and coking phases. After the cooking phase was established, the $PM_{2.5}$ emissions were consistently low, close to the instrument detection limit (0.001 mg/m^3) while the power was stable. Moreover, the refuelling operations are nearly invisible on the charts because fuel is never placed directly on the burning coke bed, but only loaded into the hopper. For this reason the fire can burn indefinitely.

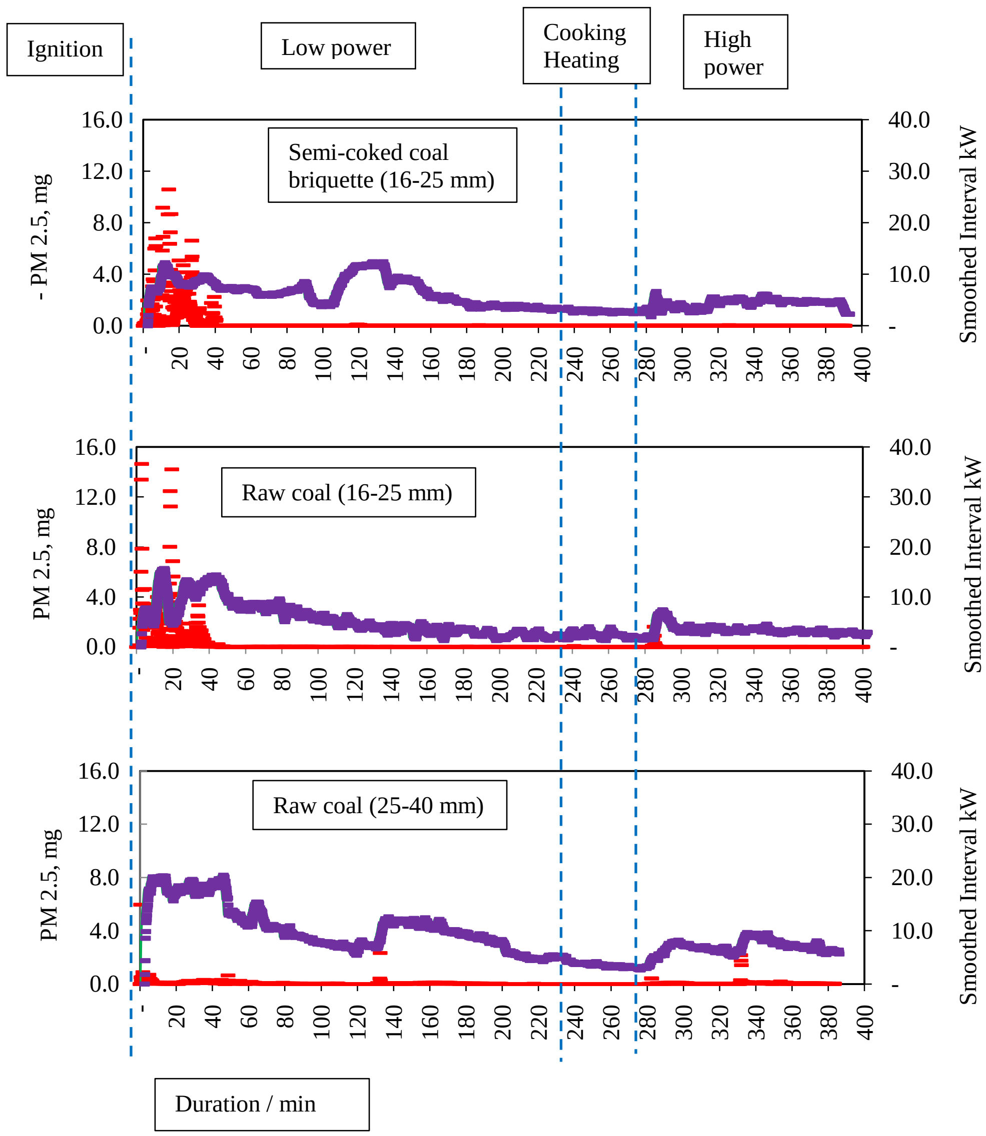


Figure 4-15: $PM_{2.5}$ emission for cross-draft (TJ4.0) stove burning different fuels

A good fire ignition method allows for the combustion conditions to improve, thus improving the combustion efficiency and lowering emissions of products of incomplete combustion. The result is a cross-draft fire that burnt at a steady rate, sustains the ideal low $PM_{2.5}$ conditions for much longer. The certain amount of wood and coal of small size was used for the good ignition. In the beginning of the ignition, the cover of hopper was opened for 10 -15 min to rise the fire and the fuel was filled into the hopper. As the results, it was properly ignited and the air was appropriately controlled to generate efficient combustion.

4.5.2 Comparison of flue gas emissions and $PM_{2.5}$ from TJ4.0 cross-draft and Chinese typical up-draft stoves burning different types of fuel

Emission can vary significantly in both qualitatively and quantitatively depending on appliance type, fuel properties and operation (Boman, et al., 2005). In most combustion systems, if primary and excess air are insufficient to complete the combustion process, unburned fuel, soot, smoke and carbon monoxide will be produced. On the other hand, too much excess air will result in cooling of fuel and combustion gases, and this also can lead lower combustion efficiency. Therefore, there is a need to provide an optimal amount of excess air.

In this study, $PM_{2.5}$, CO and CO/CO_2 ratio were measured through holes made on chimney for taking flue gas samples. All these measurements were made at 10 second intervals and stored in computer in digital form and then summarized and used for analyses. Figure 4-3 show that the comparison of the average emission factors for $PM_{2.5}$ in units g/MJ for the up-draft and cross-draft combustors using different fuels with different sizes. The emission factors are described on basis of fuel mass according to 6-hour combustion sequence.

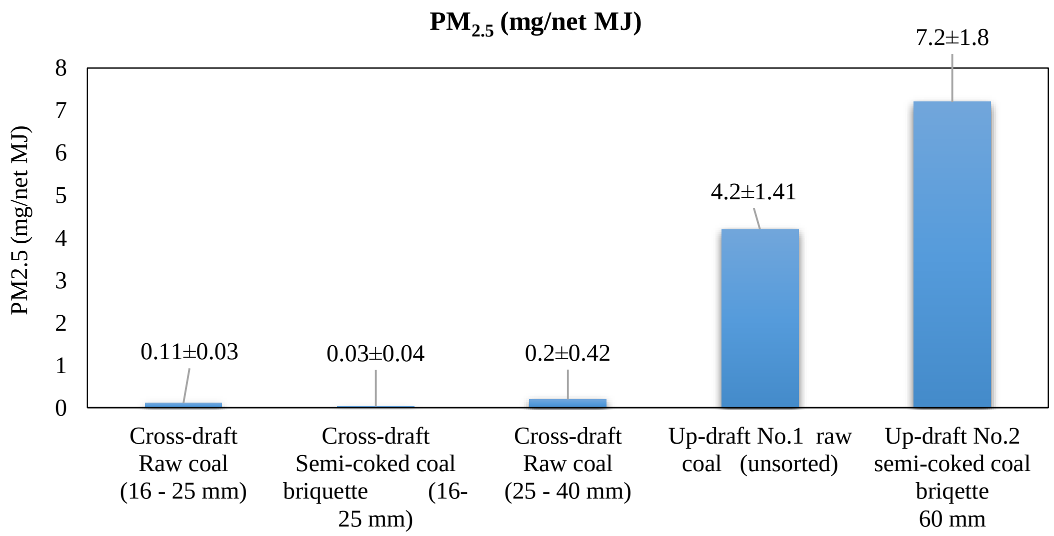


Figure 4-16: Comparison of $PM_{2.5}$ specific emission factors for the cross-draft and up-draft combustor burning different types of fuel with different sizes

The Table 4-3 shows the results of the comparison of average results of $PM_{2.5}$ emissions produced from the cross-draft and up-draft stoves burning different types of fuel. As the results, for the cross-draft stove, there is a considerable reduction in $PM_{2.5}$ produced compared with the up-draft stove. However, there was no large change between the fuel types. The $PM_{2.5}$ emission was reduced by 95 -99% on average from 0.2 mg/MJ to 0.03 mg/MJ when switching from up-draft to cross-draft stove (Table 4-3). But there is a big difference in PM produced from the up-draft from 4.2 mg/MJ to 7.2 mg/MJ burning raw coal and semi-coked coal respectively.

Table 4-7: Comparison of average results of $PM_{2.5}$ emissions of the cross-draft and up-draft stoves using different types of fuel with various size ranges

Stove type	Fuels	$PM_{2.5}$ (mg/MJ)	Difference (%)
Cross-draft vs. up-draft	Raw coal (16-25 mm)	0.11±0.03	97
	Raw coal (unsorted)	4.2±1.41	
Cross-draft vs. up-draft	Raw coal (16-25 mm)	0.11±0.03	98
	Semi-coked coal briquette (60 mm)	7.2±1.80	
Cross-draft vs. up-draft	Raw coal (25-40 mm)	0.2±0.42	95
	Raw coal (unsorted)	4.2±1.41	
Cross-draft vs. up-draft	Raw coal (25-40 mm)	0.2±0.42	97
	Semi-coked coal briquette (60 mm)	7.2±1.80	
Cross-draft vs. up-draft	Semi-coked coal briquette (16-25 mm)	0.03±0.04	99
	Semi-coked coal briquette (60 mm)	7.2±1.80	
Cross-draft vs. up-draft	Semi-coked coal briquette (16-25 mm)	0.03±0.04	99
	Raw coal (unsorted)	4.2±1.41	

The time series plots of $PM_{2.5}$ concentrations are presented in Figure 4-4 for both fuel types in the up-draft stove. The fuel types resulted in substantial changes in emissions. Both fuels resulted high peaks of emissions at the early stages as the ignition materials burned and consequently ignited the primary fuels. Although, the $PM_{2.5}$ concentration drops sharply after the fire is established the emission peaks again after refuelling during the high power phase.

In case of the up-draft stove, while the raw coal had higher emissions during ignition, the semi-coked coal made more PM when the stove was refueled and the power ramped up from low to high. In general, refueling with semi-coked coal requires doing so earlier in the burn sequence and with a greater quantity than for raw coal.

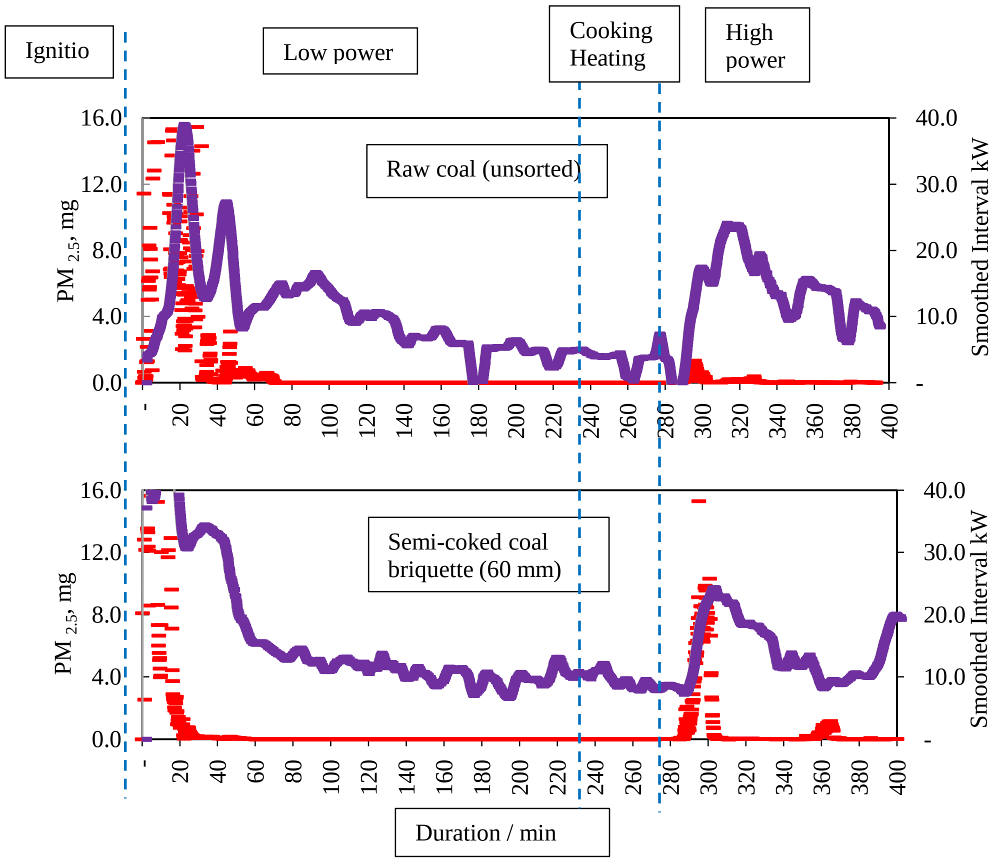


Figure 4-17: $PM_{2.5}$ emissions for all types of fuel in up-draft stove

Based on the results presented herein, it can be indicated that there is a need to consider the design and development of stove technologies which are more efficient and less polluting in order to improve combustion efficiency and more complete combustion, it has potential to contribute air pollution. The cross-draft stove is a positive step towards dealing with air pollution issues in areas which use solid fuel stoves for their energy source for heating and cooking. The government can subsidize the improvement of the heating and cooking appliances to reduce the amounts of pollution produced from domestic stoves. According to the result, the greatest amount of emissions are emitted during the beginning of fire and therefore, proper and efficient ignition techniques can contribute to decreasing air pollution. The cross-draft stove design eliminates almost entirely surges in PM emissions following refuelling and so can make important emission reductions for stoves that are kept burning continuously during winter and refuelled one several times per day.

Chapter 5 Effect of fuel type and size on CO emissions from TJ4.0 cross-draft stove

In this chapter, the effects of the fuel type and size ranges on CO emissions are presented for the TJ4.0 cross-draft stove and the results compared it with Chinese typical up-draft stove. In the first two subsections, the stove description and fuel characteristics tested in this study and results for the cross-draft stove burning two size ranges of raw coal and a smaller size of semi-coked coal briquette and up-draft stove using unsorted raw coal and semi-coked coal briquette (60 mm) are presented. This chapter ends with summary of the comparison of emission results for each stove/fuel combination and other reported emission results.

5.1 Introduction

Because of non-optimal combustion conditions by mixture of fuel and air, some substances such as CO, NO, NO_2, H_2, hydrocarbons (HC), poly-cyclic aromatic hydrocarbon (PAHs) and particulate matter are presented. Carbon monoxide is a pollutant due to incomplete combustion. Adequate air supply and optimized grate systems can significantly improve the mixing of air and combustible gases, reduce the excess air, improve the combustion process, and lower pollutant levels. If the temperature in the combustion chamber is high enough for oxidation reactions to take place. Cold air flow can reduce the reaction and consequently, increase the concentration of unburnt in flue gas (Petrocelli and Lezzi, 2013).

In this study, the experiments were conducted employing typical Chinese up-draft space heating stove burning raw coal and semi-coked coal briquettes. The stove type and ignition method are the crucial elements that affect the energy efficiency and $PM_{2.5}$ and CO emissions. The particulate emissions was unexpectedly low and heating efficiency was comparatively high in the cross-draft type (TJ4.0) than when using the Chinese typical up-draft stove. The stove performances such as heating efficiency and emission factors affected by the combustion method. In the up-draft stove, the fuel in the combustion chamber is burnt gradually from the top to down and the existence water in the fuel slowed the combustion and reduced the temperature in combustion zone, leading to less fuel gasified at any given moment. Consequently, the combustion power was reduced.

The start and finishing times for each test were recorded. The stove and pre-weighed, fuel was placed on a mass balance. The diluter and the thermocouples were installed in various locations in the chimney. The chimney was fixed such as to avoid touching the roof and the scale was switched on after the wood and fuel were prepared. The coal was crushed and screened to create the 16 - 25 mm and 25 - 40 mm fractions. All fuel to be used during the test was pre-weighed before placing it ether in the stove or on the scale. After completing the pre-test check list, the stove was ignited. (Appendix A).

5.2 Stove and Fuels

In this study TJ4.0 design as a cross-draft stove and a typical Chinese household space heating and cooking stove as an up-draft stove were selected as a baseline reference technology and tested for $PM_{2.5}$ emissions. The description of the stoves were presented in Figure 3-1 and Figure 3-2, Chapter 3.

Different types of fuel with various size ranges are tested for the cross-draft stove and up-draft stove in this study. These fuels in the TJ4.0 design as a cross-draft stove are: small raw coal (16-25 mm), large raw coal (25-40 mm) and semi-coked coal briquette (16 - 25 mm). For the up-draft stove, the fuels are: raw coal (unsorted) and semi-coked coal briquette (60 mm). Characteristics of this fuels are presented in the Table 3-1, Chapter 3.

5.3 CO specific emission factors

Carbon monoxide (CO) is a pollutant substance due to incomplete combustion and it is big issue for air pollution in many countries which is only limited by law because it is strongly related to the quality of combustion and then to the concentration of other products of incomplete combustion. The incomplete combustion is mainly caused by poor mixing of air in grate-fired systems with combustible substances both in the fuel bed and in the combustion chamber. Advanced air supply systems and optimized grate systems can significantly enhance the mixing, reduce the excess air, improve the combustion process, and lower pollutant levels. Another crucial parameter for the complete combustion is temperature of the combustion chamber. If temperature is higher enough to allow for oxidation reactions, the combustion will take place more completely. Cold air streams or drafts, for instance as secondary air, or the contact between flame and cold walls can stop the reaction and, consequently, increase the concentration of unburnt in flue gas. Combustion quality is also influenced by the residence time of gases in high temperature zone: combustion at low temperatures requires a longer residence time (Petrocelli et al., 2014).

All gaseous compounds including CO_2, CO, O_2, NO_x and SO_2 emitted from combustion of the fuels are measured by using the “VARIO PLUS” gas analyzer. Gas flows are controlled with X-Stream device. The flue gases are diluted with mixing with air supplied by a compressor. Based on the ratio between CO_2 gas concentrations in the diluted and undiluted gas streams, the dilution amount of the particulate gas stream is calculated.

Specific emission factors are expressed in units (mg/kg) or (mg/MJ) for CO emissions. Equation defining the specific emission factors are presented according to the Heterogeneous Stove Testing Protocol.

Specific emission factor for CO (cooking):

$$E_{CO}^{C} = m_{CO}/(Q_P \times \eta_c) \qquad \text{(Eq. 5-1)}$$

E_{CO}^{c} = specific emission factor for CO, referenced to useful heat delivered to pot (g/MJ)

m_{CO} = mass of pollutant emitted over complete burn sequence, as defined for CO (g)

Q_P = heat delivered to the pot (J) (Equation 2-2)

η_c = cooking efficiency (%) (Equation 2-1)

Specific emission factor for CO (heating):

$$E_{CO}^{h} = m_{CO}/(Q_R \times \eta_h) \quad \text{(Eq.5-2)}$$

Where,

E_{CO}^{h} = specific emission factor for CO, referenced to useful heat delivered to room (g/MJ)

m_{CO} = mass of pollutant emitted over complete burn sequence, as defined for CO (g)

Q_R = heat content of fuel and kindling = $(B_F \times Q_{LHVf} + B_i \times Q_{LHVi})$ (MJ)

η_h = heating efficiency (%) (Equation 2-6)

The carbon-monoxide (CO) is calculated as follows:

CO = Mass of CO (per MJ) / thermal efficiency (g/Net Megajoule)

(1) CO per standard m3 in the stack gases is expressed by CO concentration in the stack, Excess Air

(2) Volume of stack gases, standard m^3's is expressed by stoichiometric air demand, mass burned

(3) Mass of CO emitted is expressed by CO per standard m^3 in the stack gases and volume of stack gases

(4) Heat produced is expressed by fuel mass burned and heat content of fuel per kg

(5) Mass of CO per MJ is expressed by mass of CO emitted and heat produced

(6) Heat lost (thermal and chemical) is expressed by EA chimney, chimney temperature and CO level

(7) Heat gained is expressed by heat produced and heat lost

(8) Thermal efficiency is expressed by heat gained and heat produced

(9) CO per Net MegaJoule is expressed by mass of CO per MJ and thermal efficiency

The data collection and calculation are same in the Chapter 4 when employing cross-draft stove for testing.

5.4 Results and Discussions

5.4.1 CO emission factors in cross-draft stove

The emission factor CO (EF), expressed in ppm (v), is the measured CO concentration multiplied by the total air supply (λ). It gives the calculated CO concentration of a standard cubic meter of combustion gases containing 0% O_2 (i.e. zero excess air). For any given fuel there is a CO_2 Maximum potential stack concentration. For each CO_2 Max there is a CO (EF) that represents a CO/CO_2 ratio of 2%, a common CO emission limit.

Carbon monoxide emission factors for each fuel and stove combination are presented in Table 5-1. The emission factors are based on whole testing sequence, from ignition phase to four hours low power elapsed and then refuelling after that the fuel burnout. The results shows that there is not significant difference on CO emission between all type of fuels with different sizes in the cross-draft heating and cooking appliance. When burning large raw coal (25-40 mm), CO emission decreased by 29-38% on average 0.5 g/MJ than burning small raw coal (16-25 mm) and semi-coked coal briquette (16-25 mm) on average by 0.7 g/MJ and 0.8 g/MJ respectively. But for fuel particle sizes in the cross-draft did not influence largely on the CO emission for small sized raw coal and bigger sized raw coal and semi-coked coal briquette.

Table 5-8: Comparison of average results of CO emission for all fuels in the cross-draft stove

Fuels	Stove type	CO (g/MJ)	Relative difference (A-B)/A (%)
A) Raw coal (16-25mm) vs.	Cross-draft	0.7±0.3	29
B) Raw coal (25-40mm)		0.5±0.2	
A) Semi-coked coal briquette (16-25mm) vs.	Cross-draft	0.8±0.4	13
B) Raw coal (16-25mm)		0.7±0.3	
A) Semi-coked coal briquette (16-25mm) vs.	Cross-draft	0.8±0.4	38
B) Raw coal (25-40mm)		0.5±0.2	

Time series plots carbon monoxide generated from all three fuels for the cross-draft stove are shown in the Figure 5-1.

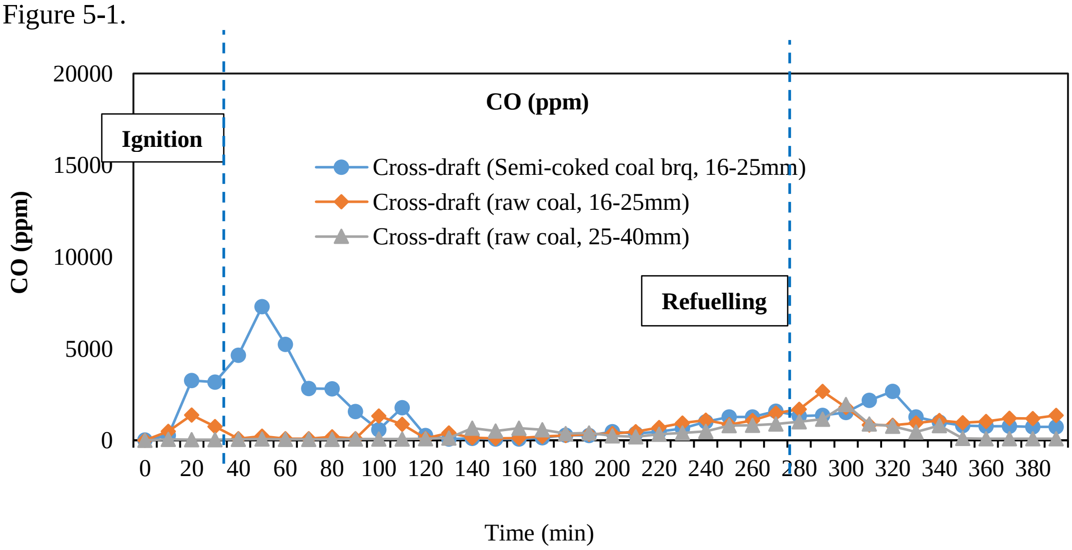


Figure 5-18: CO emission for cross-draft (TJ4.0) stove burning different fuels

The CO time plots for the semi-coked coal briquettes and the raw coal are distinctly different during the ignition phase. For the semi-coked coal briquettes, the CO emissions increase slowly over the first 45 min and then decrease again reaching a low stable baseline value after 90 min (the Y-axis scale is deliberately set at 20 000 ppm CO to keep consistent with CO time-plots for other stove graphs in the sections above). With regards to the effect different coal sizes on emissions, the small and large raw coal resulted similar low emission profiles during ignition. The stove was refuelled at approximately 240 min (3 h), as indicated by the arrows in the figure. As the new fuel reached the pyrolysis stage, there were slight increases of CO over a long period, extending to 340 min. All three fuels behaved similarly during refuelling. Of note there is no share increase during the later stages of fuel burnout extending to 400 min (almost seven hours) after ignition.

5.4.2 CO/CO_2 ratio in cross-draft stove

CO/CO_2 ratio is an expression of the stove combustion efficiency. The lower this ratio, the more complete the combustion taking place in the stove. Results of influence of different kinds of fuels on the CO/CO_2 ratio in the cross-draft stove are shown in Figure 5-2. The low CO/CO_2 ratio is a result of good air to fuel mix through the use of optimized primary and secondary air during the coking process resulting in more complete combustion. The time plots in Figure 5-2 for the cross-draft stove showed that CO/CO_2 was on average of 2.1% at low power phase, 4.3% at the cooking phase and 2.0% at the high power phase for the semi-coked coal briquette. At cooking phase, the CO/CO_2 ratio was higher than the other phases because of the refuelling. In case of small raw coal, the ratio was 1.3%, 6% and 3% at low, cooking and high phases respectively. The lowest ratio was for large raw coal and it was 1%, 2.9% and 0.5% at low, cooking and high power phases respectively because there was hot ignition in the stove.

In addition, the cross-draft stove (TJ4.0) resulted a CO/CO_2 ratio was less than 1% during the low power phase. Although for all fuels, increasing excess air cools the fire, CO /CO_2 ratio increases at the ignition phase and at refueling. The reason is that the fuel was not covering the front of the grate allowing too much air to pass through. With the 25-40 mm fuel this effect was much less pronounced because of the hot ignition.

The comparison of average of CO/CO_2 ratio for cross-draft stove burning various fuels with different fuel sizes which were tested in this study is presented in Table 5-2.

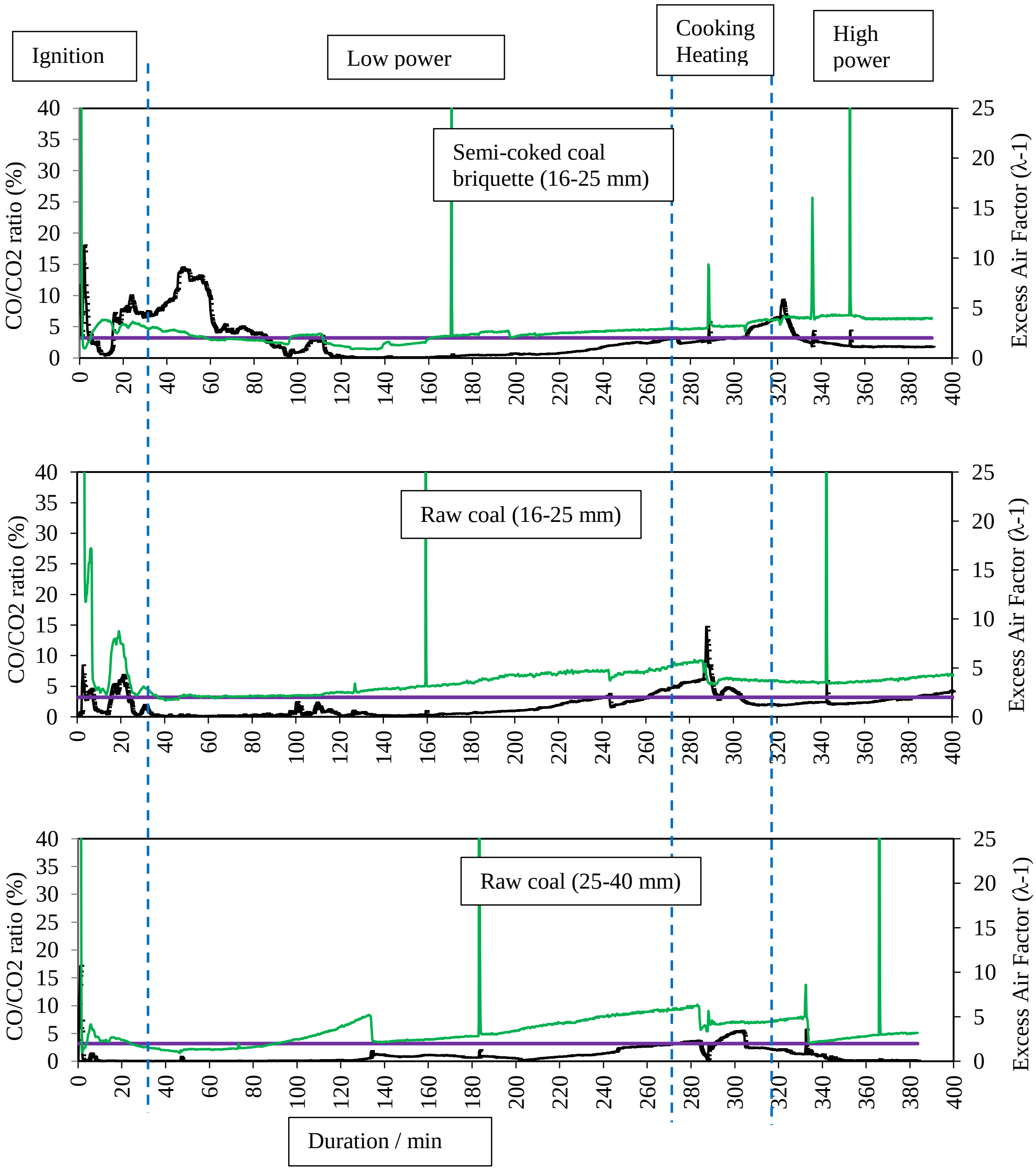


Figure 5-19: CO/CO_2 ratio for all three fuels in the cross-draft (TJ4.0) stove

Table 5-9: Comparison of average results of CO/CO_2 ratios for all fuels in the cross-draft stove

Fuels	Stove type	CO/CO_2 (%)	Relative difference (A-B)/A (%)
A) Raw coal (16-25mm) vs.	Cross-draft	1.9±0.9	44
B) Raw coal (25-40mm)		1.1±0.5	
A) Semi-coked coal briquette (16-25mm) vs.	Cross-draft	2.9±1.6	34
B) Raw coal (16-25mm)		1.9±0.9	
A) Semi-coked coal briquette (16-25mm) vs.	Cross-draft	2.9±1.6	63
B) Raw coal (25-40mm)		1.1±0.5	

The Table 5-2 shows that there is no significant difference for fuel particle size ranges in cross-draft stove. However, the more changes of the ratio were observed between large raw coal and semi-coked coal briquette. Because the stove was tested at the hot ignition when burning large raw coal. The semi-coked coal briquette led to increases in the CO/CO_2 ratio by 34 to 63% respectively compared with both raw coals. Also, the large raw coal resulted in a decrease in the ratio by 44% compared with the small raw coal. But the average results were at less than 2% during whole testing sequence. It is expected that all three fuels was properly combusted, in controlling right air flow in cross-draft combustor.

5.4.3 Comparison of CO emissions and CO/CO_2 ratio from cross-draft and up-draft stoves burning different types of fuel with various size ranges

In this study, CO and CO/CO_2 ratio were measured through holes made on chimney for taking flue gas samples. All these measurements were made at 10 second intervals and stored in computer in digital form and then summarized and used for analyses. Figure 5-3 shows that the comparison of the average emission factors for CO (g/MJ) for the up-draft and cross-draft combustors using different fuels with different sizes respectively. The emission factors are described on basis of fuel mass according to 6-hour combustion sequence.

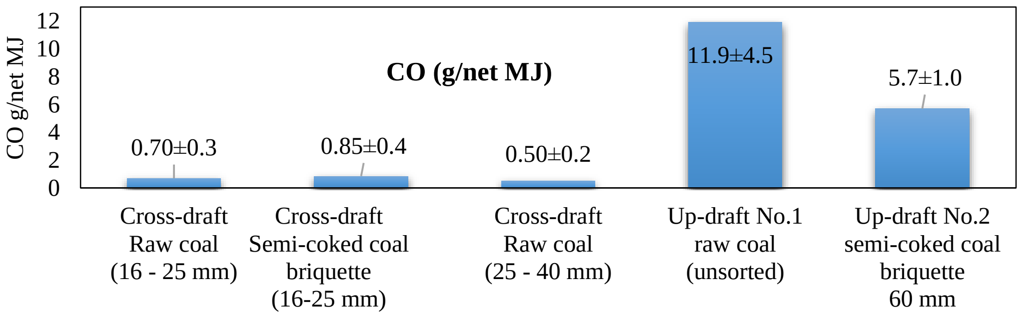


Figure 5-20: Comparison of CO emission for the cross-draft and up-draft combustor burning different type of fuels with different sizes

As the result of Figure 5-3, the CO specific emission factors generated from up-draft combustor emitted more than cross-draft combustor because of different kind of combustion system. At the beginning of the test, it was properly ignited.

The Table 5-3 shows the results of the comparison of average results of CO emissions and the CO/CO_2 ratio produced from the cross-draft and up-draft stoves burning different types of fuel. The results showed that a change in the stove type caused large differences on the CO emissions. When employing the TJ4.0 instead of the up-draft stove, CO emission decreased by 86 - 96% respectively when burning different fuels. But the fuel particle sizes in the cross-draft did not have a large influence on the CO emission for either small or large sized raw coal, or for semi-coked coal briquette. For CO/CO_2 ratios, when the cross-draft stove burns both raw coals the ratio was decreased by 64% - 84% on average compared with the up-draft stove, from 1.9% and 1.1%. In case of semi-coked coal in the cross draft stove, the CO/CO_2 was less by 46 -56% at 2.9% than the up-draft stove at 5.4% and 6.5% for semi-coked coal briquette and raw coal respectively.

Table 5-10: Comparison of average results of CO emissions and the CO/CO_2 ratio of the cross-draft and up-draft stoves using different types of fuel with various size ranges

Stove type	Fuels	CO (g/MJ)	Difference (%)	CO/CO_2 (%)	Difference (%)
Cross-draft	Raw coal (16-25 mm)	0.7±0.30	94	1.90±0.9	71
vs. up-draft	Raw coal (unsorted)	11.9±4.53		6.54±2.1	
Cross-draft	Raw coal (16-25 mm)	0.7±0.30	88	1.90±0.9	64
vs. up-draft	Semi-coked coal briquette (60 mm)	5.7±1.00		5.35±0.8	
Cross-draft	Raw coal (25-40 mm)	0.5±0.21	96	1.06±0.5	84
vs. up-draft	Raw coal (unsorted)	11.9±4.53		6.54±2.1	
Cross-draft	Raw coal (25-40 mm)	0.5±0.21	91	1.06±0.5	80
vs. up-draft	Semi-coked coal briquette (60 mm)	5.7±1.00		5.35±0.8	
Cross-draft	Semi-coked coal briquette (16-25 mm)	0.8±0.42	86	2.89±1.6	46
vs. up-draft	Semi-coked coal briquette (60 mm)	5.7±1.00		5.35±0.8	
Cross-draft	Semi-coked coal briquette (16-25 mm)	0.8±0.42	93	2.89±1.6	56
vs. up-draft	Raw coal (unsorted)	11.9±4.53		6.54±2.1	

Time series plots carbon monoxide generated from all type of fuels in the up-draft stove are shown in the Figure 5-4.

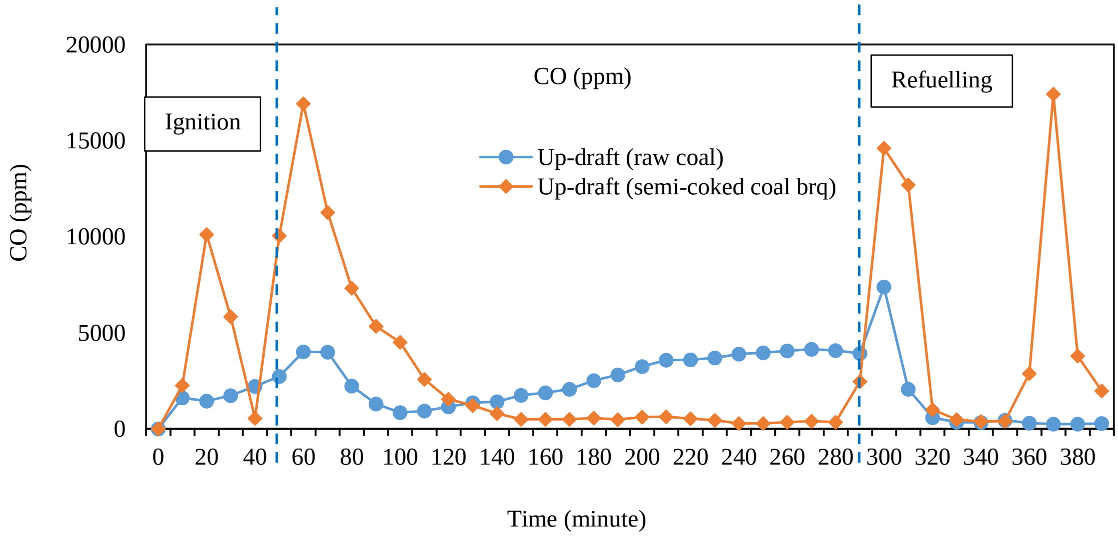


Figure 5-21: CO emissions for all two types of fuel in up-draft stove

Figure 5-4 shows that when semi-coked coal briquette was used in the up-draft stove, the CO emissions were high and variable during the first 100 min, where after they dropped to a low baseline value until the stove was refuelled at 290 and 360 min, when the CO emissions increased to over 15,000 ppm for 20 min before settling again to low values. In contrast, when using raw coal, CO increased slowly after ignition but remained above baseline for most of the sequence with a short spike on refuelling at 290 min. Except for the refuelling spike, the values remained at or below 4,000 ppm.

It shows that there is large difference of combustion process in the different combustion chamber. It has a potential reason for the increase in CO emissions in up-draft stove, the fire is smouldered for long time. Since the ash formed around the coked coal, the appliance emits large quantities of CO because of there is not enough hot coke to sustain CO burning flame due to the inadequate air flow for complete combustion, where its has harmful impact to the surroundings (Pemberton-Pigott et al., 2009).

The combustion efficiency is determined by the quality of the mixture of fuel and air to produce complete combustion in the burner. In other words, the combustion efficiency expressed by the CO/CO_2 ratio and how well the fuel burned in combustion process.

The influence of the ratio of different types of fuel in the up-draft stove is shown in Figure 5-5.

The Figure 5-5 shows that in case of the up-draft stove, the raw coal burns furiously with high power in the beginning then collapses into a dying fire with increasingly higher CO/CO_2 ratio as evidenced by the increasing excess air level. With the semi-coked coal briquettes, the fuel burns much more evenly as it is harder and denser than the raw coal. The low volatiles level also contributes to the low burn rate. The three spikes in CO are caused by the refueling operations when new fuel is placed on top of the fire, greatly increasing the PM and CO level, until the fire again stabilizes. All volatiles and combustible gases must pass the combustion chamber to get turbulent, high temperature flame with lower excess air. The combustion efficiency was decreased during the smouldering phases in increasing the incomplete combustion.

The experiments conducted in the up-draft stove showed that particulate matter pollutants emitted highly at the ignition phase to compare with the pyrolysis and coking phases of combustion. As the tests, during the pyrolysis phase/low power fire phase the emissions was low, but when the fuel was refueled before the cooking phase the smoke was emitted highly again because of the fuel put on the hot surface of fire. This is the main reason that the smoke in the up-draft stove was at higher during testing sequence than the cross-draft.

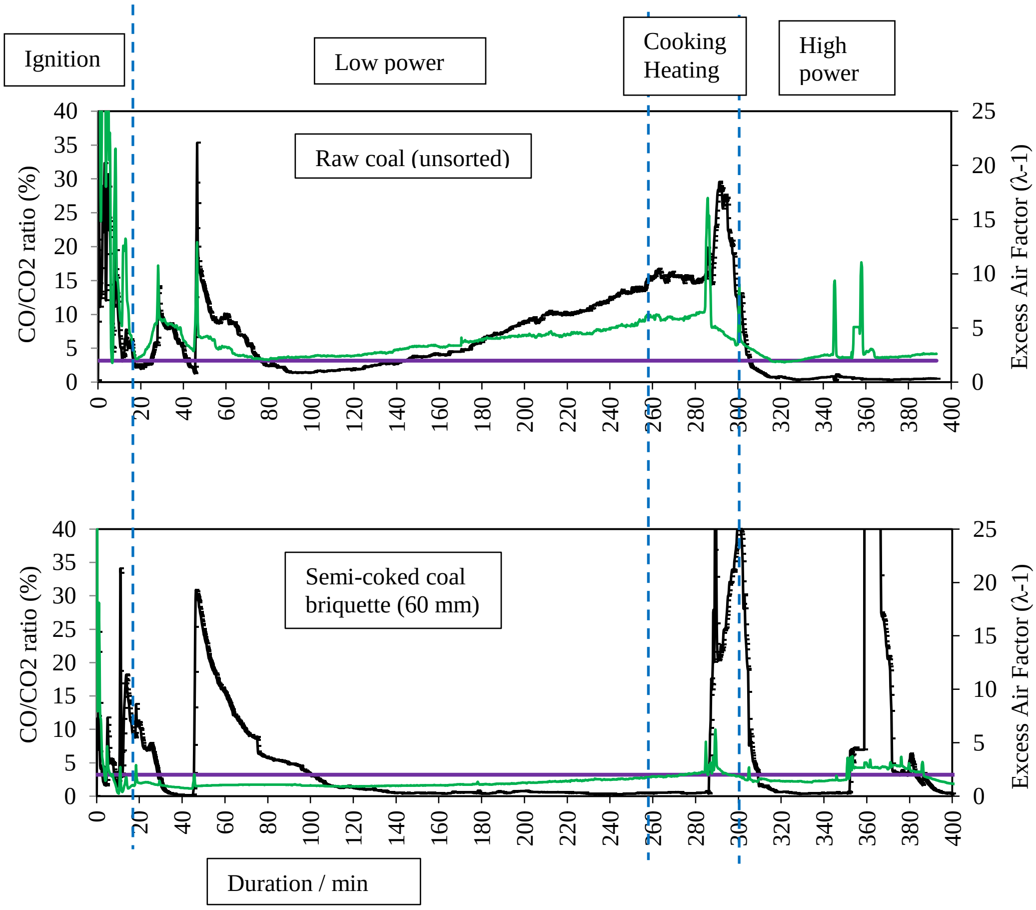


Figure 5-22: CO/CO_2 ratio for the up-draft stove burning different types of fuel

5.4.4 Comparison of CO and $PM_{2.5}$ emission factors from cross-draft and up-draft stoves burning different types of fuel with other reported

There are many researchers conducted the experiments for different types of heating and cooking appliances burning various fuels. The comparison of the results for TJ4.0 and up-draft stoves which are tested in this study with another results performed from other publications is presented Table 5-4.

Table 5-11: The comparison of performance results of the cross-draft and up-draft stove with other reported.

Stove types	Fuel types	Energy efficiency (%)	$PM_{2.5}$ emission (mg/MJ)	CO emission (g/MJ)	References
Chinese improved stove	Raw coal	13.9	2.67±2.68	33.6±15.7	(Shen et al., 2015)
	Coal briquettes	32.4	1.05±0.86	8.22±5.63	
Pellet boiler	Pellet	-	6.0	47	(Jalava et al., 2012)
Imbawula cooking stove	Large coal (60-80 mm)	-	0.75±0.04	4.3±0.22	(Masondo et al., 2016)
	Medium coal (40-60 mm)		0.31±0.02	1.6±0.09	

	Small coal (20-40 mm)		0.42±0.06	1.5±0.04	
	Large coal (25-40 mm)	85.4±0.57	0.2±0.42	0.5±0.21	
Cross-draft stove (TJ4.0)	Small coal (16-25 mm)	90.7±3.96	0.11±0.03	0.7±0.30	This study
	Semi-coked coal briquette (16-25 mm)	93.1±1.34	0.03±0.04	0.8±0.42	
Up-draft stove (Chinese typical stove)	Raw coal (unsorted)	69.2±2.69	4.2±1.41	11.9±4.53	This study
	Semi-coked coal briquette (60 mm)	56.3±0.64	7.2±1.80	5.7±1.00	

The results shows that the highest efficiency was obtained by 85.4% to 93.1% on average from the cross-draft stove burning different fuels with different sizes to compared with others. As the result presented in this Figure, the pellet boiler, Chinese improved stove and up-draft stove was emitted higher on $PM_{2.5}$ and emissions by 6 mg/MJ, 2.67-1.05 mg/MJ and 4.2-7.2 mg/MJ burning both pellet, raw coal and coal briquettes respectively than the TJ4.0 stove. For TJ4.0 stove these emission was at the lowest level on average by 0.2-0.03 mg/MJ using both raw coals and coal briquettes. CO emission from pellet stove was emitted higher than others. There is no significant difference on $PM_{2.5}$ emission from the Imbawula cooking stove and TJ4.0 cross-draft stove. However, for CO emission, the Imbawula stove emitted much more than the cross-draft stove.

In general, particulate and CO emission factors depend on the various factors and specially, it influences the stove type and operation condition. As the result, same fuels such as raw coal and coal briquette were fed into the combustors despite the pellet stove. But the change in the performance results of the different stoves was shown largely.

Chapter 6 Conclusion and Recommendations

6.1 Conclusions

In the past there have been several studies on emissions from solid fuel appliances. Generally, residential coal appliances are poorly designed and produced large quantities of fine particle matter and hazardous gases. This research is intended to develop a low emissions combustor technology and provided detailed information about particulate emissions from solid fuel combustion that can be used in the development of combustion technologies that generate less particulate matter, but make use of commonly available and affordable solid fuels.

In this work a laboratory-based investigation was made using an ultra-low emissions cross-draft coal gasifier (stove name - TJ4.0) to determine the particulate $PM_{2.5}$ and CO emission factors during the combustion of a range of fuels.

Results of the study indicated that the fuel particle sizes in the cross-draft did not have a large influence on CO, $PM_{2.5}$ pollutants and CO/CO_2 ratio, for raw coal of small size (16 -25 mm) and large size (25-40 mm) and semi-coked coal briquette of 16 -25 mm. Even though, there was large difference between the TJ4.0 cross-draft and Chinese typical up-draft stoves in CO and $PM_{2.5}$ emissions. The $PM_{2.5}$ emissions were reduced by 95 - 97% and CO was decreased by 86 - 96% when switching from up-draft to cross-draft stove burning different fuels. Moreover, as the result of these experiments, the thermal efficiency for the TJ4.0 cross-draft stove is demonstrated to be higher than a typical Chinese up-draft chosen as a reference device. For example, the heating efficiency was higher on average by 21% in the TJ4.0 cross-draft combustor than in the Chinese typical up-draft stove in case of raw coal. For semi-coked coal briquette, there was 39.5% decrease in heating efficiency for the up-draft space heating stove in comparison with the TJ4.0 cross-draft stove

The technical experiments were found that the gaseous and particle emissions were dependent on the different combustion conditions of the stove chamber. When employing the cross-draft type, no smoke was throughout the whole burning sequence if the fire had been properly ignited. This indicated that the stove is well designed, the combustion process is nearly ideal with the result that the PM emissions are extremely low. In addition the stove is equipped with a suitably sized heat exchanger, fuel hopper, grate and other design elements. The fuel is supplied once during the whole test according to the 6-hour testing sequence. The high thermal efficiency indicates this product will save fuel compared with existing popular models.

6.2 Recommendations

A results of PM and CO emissions from the solid fuel combustion is harm for human health and air pollution, especially in the winter season in both developing and developed countries. Combustion from space heating and cooking stoves contributes to the many diseases already affecting large percentage of Mongolian, Chinese and other populations worldwide. The reduction of PM and CO emissions a necessity for achieving satisfactory health outcomes should be followed several strategies, such as, the improvement in the design and development of efficient and less polluting stoves. Although, the designs should be based on sound scientific and engineering grounds, designs ought to take into account the culture and social habits and preferences of potential user communities. Moreover, improved designs need to be energy efficient to reduce fuel consumption during cold winter periods.

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JARGALSAIKHAN ALTANZUL

Beijing, China, May 2017

Appendix: Checklist for stove testing

A1. Preparation for a test up to the point of ignition

1.1. Turn on Xstream Gas Analyser one hour before the test start.

1.2 Check size and amount of coal, prepare enough coal of appropriate size for current test.

1.3 Check size and amount of wood, prepare enough wood of appropriate size for current test.

1.4 Turn on PM sampler DRX pull of the gas tube, insert the Zero Filter and perform a zero test.

1.5 Remove the Zero Filter and insert the tube from the Test Room. Push the Start button on the DRX and measure ambient air PM level for more than 10 min. Press the Graph button and record the Average PM number indicated on the bottom of the screen.

1.6 Turn on computer, check that is working properly.

1.7 Turn on the fuel scale and stove scale.

1.8 Place the stove on the scale. Position the stove centrally so the load cell is equally stressed.

1.9 Check that the anticipated total mass will be less than 150 kg when fuelled and ready to go. Consider that a pot with 10 litres of water may be added during some tests. If the capacity of the scale will not be exceeded, proceed with the setup.

1.10 Place the chimney and diluter assembly on the chimney connecting pipe. Make whatever arrangements are necessary to stabilize the chimney so that during the test it will not touch the roof hole.

1.11 On the blackboard, write the test number, current date, the stove name, manufacturer's name.

1.12 Weigh the coal that will be used during the test on the Fuel Scale and place it on the Stove Scale in a manner that it will not be affected by heat from the stove.

1.13 Write the total weight of the coal placed on the Fuel Scale on the blackboard.

1.14 Weigh the wood and ignition kindling needed using the Fuel Scale and place it on the Stove Scale. Fuel needed for refueling must also be on the Stove Scale when the test commences.

1.15 Write the total weight of the wood placed on the Fuel Scale on the blackboard.

1.16 Preparing to light: Load the wood and coal into the stove and set the kindling ready to ignite.

1.17 Place the thermocouples in position, or in certain cases, near the position they will be in when the fire is ignited. The must be on the Stove Scale so the total initial mass can be recorded.

1.18 Check that the stove is prepared on the bench and thermocouples and gas sample tubes are in place and that the chimney-mounted ones are not touching the building.

1.19 Thermocouple 101 – outside Station 1.

1.20 Thermocouple T2~1 is placed with the tip 50mm below the cooking surface near the center of the fire.

1.21 Thermocouple T3~1 is placed near the centre of the cooking surface.

1.22 Thermocouple T4~1 is placed inside the heat exchanger.

1.23 Thermocouple T5~1 is placed at the gas exit point from stove or the base of the chimney.

1.24 Thermocouple T6~1 is placed in the stack at the roof line, defined as the point after which all heat is wasted.

1.25 If a combustion analyser such as a Testo is used for gas measurements, the thermocouple in the sample hose will be designated T6~2.

1.26 Thermocouple T7~ is placed in the stack at the top of the chimney.

1.27 Additional thermocouples may be added as required, giving each workstation an appropriate number. For example low pressure boiler systems may have several measurement points.

1.28 Check stability of the Stove Scale, the chimney placement and stability of the Stove Scale readings.

1.29 Read and record The Stove Scale mass just before ignition. Record the initial mass on the blackboard.

1.30 Check that the gas sample and diluter air supply tubes are in place.

1.31 Prepare match and diesel for lighting. Do not light the fire!

1.32 Turn on Pump 1, Pump 2 and Pump 3.

1.33 Set the Air/Stack Gas Lever 1 into the Stack Gas position (down).

1.34 Set the Air/Stack Gas Lever 2 into the Diluter Gas position (down).

1.35 Switch the Calibrate/Air Handle 3 to the Air position.

1.36 Switch the Calibration selector handle to the appropriate gas if performing a gas cell calibration.

1.37 Check Red Channel flow meters: Stack Vacuum Flow = ±250 l/hr and Stack Gas Flow ± 90 l/hr.

1.38 Check Blue Channel flow meters: Diluter Vacuum Flow = ±250 l/hr and Stack Gas Flow ± 90 l/hr.

1.39 Check White Channel flow meters: Air Vacuum Flow = ±300 l/hr and Stack Gas Flow ± 200 l/hr.

1.40 Check Red channel Vacuum Pressure = ±0.5.

1.41 Check Blue channel Vacuum Pressure = ±0.5.

1.42 Check White channel Vacuum Pressure = ±0.5.

1.43 Check Red Channel gas pressure gauge = 3.0 P.S.I.

1.44 Check Blue Channel gas pressure gauge = 3.0 P.S.I.

1.45 Check that the White Channel air pressure gauge is showing some pressure, normally it is between 20 and 40 P.S.I.

1.46 Stop The Dusttrak DRX recording and read the average PM reading on the Graph Screen. Record the value on the blackboard as the Initial Ambient Air PM level.

1.47 Remove the Test Room air tube and put in the Diluter Gas Tube (no. 501). Start the Dusttrak DRX, and see that it is measuring.

1.48 Start Internet Explorer and Logon to the XStream Gas analyser at address 10.168.3.5.

1.49 Move the Red and Blue Channel Air/Gas selector levers UP to select AIR. Check the gas readings on all 4 channels. If calibration is required, go to Appendix “Gas Calibration”.

1.50 Go to the “CONFIGURE”/SPECIAL/DATA LOGGER tab and Login. Check that the “OPERATION” light is GREEN. If not, press the CHANGE button. If the OPERATION light changes to GREEN, return to the OVERVIEW tab.

1.51 Start the Digital Scale Capture (DCS) programme for the Stove Scale. Open the CONFIG tab. Enter the Test number and Stove’ short form name in the ‘Pre:” window. Enter the Stove Name in the ‘Window Title’ window. Return to the DISPLAY tab.

1.52 Press the CHART button to load the Charts. Place the two windows on the monitors in an appropriate position. Check that the RECORD button reads “PAUSE RECORD” and is RED in colour.

1.53 Press the START button. Check that the REC. BUF (recording buffer) is receiving information and counting rapidly (usually to about 580 readings). Check that the “SAVED” data counter next to the PAUSE RECORD button is increasing.

1.54 Enter the LHV for the fuel in the kJ/g window by typing or using the ‘spin wheel’.

1.55 Turn on the Agilent 34972A Data Logger. Check to see that the red “MEM” is lighted. If it is not, it means there is no USB memory stick plugged into the back.

1.56 Start the Benchlink Data Logger 3 programme. Select the “Scan and Log Data” tab. Press the START button, then the OK button on the pop-up screen. Select the “Quick Graph” tab.

1.57 Click on the “Preferences” tab on the lower left. Check the box titled “Show Data Table Popup”. Press OK. Move the data popup window to an appropriate position on the screen. Set the “Scale X-Axis (Time)” to 4 min. Temperature plots should be visible on the screen.

1.58 Check that the SCAN sign is illuminated and the red “MEM” light is flashing. The display will be counting down from 10 to 0 then a recording is made.

1.59 Final gas and air flow check: Red Channel = 90, Blue channel = 90, Diluter = 200, Gas Pressures = 3 P.S.I.

1.60 Write the Initial mass on the blackboard (repeat step 20) and write down the Start Time.

1.61 Put a little diesel to the wood into the stove. Light the fire. Place the flame temperature and surface temperature thermocouples in position (if necessary) and see that the tip of the surface temperature probe us under the metal weight used to secure it.

1.62 Immediately watch the Dusttrak DRX readings. Increase the dilution if the reading reaches 120 mg/m3. If the PM reading drops below 1.0 the dilution can be reduced.

1.63 Do not reduce the dilution air flow to less than 100 l/hr.

A2. Monitoring a test

Monitor the following:

2.1 PM Measurement (<120).

2.2 Gas pressure gauges (3 P.S.I.).

2.3 Red and Blue channel flow rate (90 l/hr).

2.4 Stove Scale measurement buffer (should be running).

2.5 The XStream data logger file recording is taking place. The “Last Message” line should read “Export data logger samples to file”.

A3. Ending a test

3.1 Stop measurement when 90% of ash free fuel is burnt out. For example, if the total coal=6 054 g, and wood=345 g then net weight of fuel is 6399g. If ash is 8% then the ash free fuel is=5 887g.

If the starting weight of system was 91436 g then ending the measurements weight will be 87138 g.

3.2 Stop the Xstream gas analyser: Go to the “CONFIGURE”/SPECIAL/DATA LOGGER. Press the CHANGE button. Press View data button, get the file sheet, then copy it to the EXCEL sheet and save it into the TEST/LIBARARY folder, naming (See naming…).

3.3 Set the Air/Stack Gas Lever 1 into the air position (up).

3.4 Set the Air/Stack Gas Lever 2 into the air position (up).

3.5 Stop Stove Scale measurement by pressing STOP button on the Scale window. The data will be saved on the AUTO SAVE folder and the programme will be closed.

3.6 Stop temperature measurement by pressing the stop button on the Temperature Benchlink window, data will be autosaved in the AUTO SAVE folder, copy to test/LIBARARY, change name gas to temperature.

3.7 Stop Dustrak DRX pushing stop button on the DRX and then press YES.

3.8 Confirm that the XStream O2 cell reads about 21% (pure air).

3.9 Set the Air/Stack Gas Lever 1 into the Stack Gas position (down).

3.10 Set the Air/Stack Gas Lever 2 into the Diluter Gas position (down).

3.11 Start the TSI TrakPro software:

a) Select Instrument Setup/Communications/IP ADRESS.

b) Enter 10.168.3.4 into the bottom window and press <ENTER>.

c) If communication is successful, a green message will appear in the second window down. Press the CLOSE button.

d) Select File/Receive. It will load the files from the DRX.

e) Select the test(s) you want downloaded – usually the last one at the bottom of the list. Press the RECEIVE button. Press the CLOSE button.

f) Select File/Export/Export Test Data. Choose the test exported. Select “Tab” as the file format. Press the EXPORT button.

g) Choose the destination folder as D: User\TESTS\4 Particulate Auto-Saved Data.

h) Enter the appropriate file name in the format [Test No.] [PARTICLES] [Stove’s short name] [yyyy-mm-dd].[File type] <ENTER>.

i) Close the TrakPro programme.

3.12 Open the TESTS folder. There are 4 Auto-saved folders at the top. Open each folder and copy current file to the relevant \Library of Tests\[Test No.] folder (the test in question) and change after creating the copy, rename it according to File Naming system. For example the files from test 130 should be in the …\TESTS\Library of Tests\130.

3.13 Check the [Test No.] folder to see if there are four files, one each for the Scale, Gases, Temperatures and Particles.

3.14 Set the Air/Stack Gas Lever 1 into the Stack Gas position (down).

3.15 Set the Air/Stack Gas Lever 2 into the Diluter Gas position (down).

3.16 Turn off Pump 1, Pump 2 and Pump 3.

Turn off DRX, Xstream Gas analyser, Agilent Data logger and Scales.

Resume

Personal details:

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