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Abstract

A two-stage solid fuel research furnace was used to examine the claim that through forced draught greater mixing and more complete combustion could be achieved. By varying the primary air (PA) and secondary air (SA) flow the influence on the combustion process was investigated. In the first part of the combustion, when the release of volatile compounds predominates, the variation of neither PA nor SA had a significant influence. In the second part when mainly char is oxidised an increase in both PA and SA lead to a rising nominal combustion efficiency (NCE = $CO_2/(CO_2 + CO)$), with a greater impact observed with SA. Furthermore higher air flows caused the heat transfer, to a pot above the furnace, to decline. Therefore forced draught does lead to greater mixing and mitigation of emissions, but in the presented configuration a trade-off between a higher NCE and a lower heat transfer needs consideration.

Keywords:

Cookstove, Forced Air, Combustion

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1. Introduction

Currently, and consistently over the last three decades, 2.9 billion people rely on solid fuels as a primary source for cooking (Bonjour et al., 2013). Traditional open fires or basic cookstoves, that are primarily used for burning solid fuels, result in the emission of significant amounts of toxic products of incomplete combustion leading to health, social, and environmental problems. Worldwide, household air pollution from solid fuels is a major contributor to the burden of disease, especially for women, for whom it is second only to high blood pressure in disability-adjusted-life-years (Lim, 2012), and children, for whom it is responsible for 50% of premature deaths under five years of age (WHO, 2014). Addressing the issue of pollution from open fires and basic cookstoves is therefore important to help improve the quality of life for billions of people.

To reduce the problems related to traditional cooking methods there are a multitude of improved cooking systems on the market (Urmee and Gyamfi, 2014), with some showing promising results (Johnson et al., 2013; Jetter et al., 2012). However, as noted by MacCarty et al. (2010), not all new stove designs necessarily improve the emission of products of incomplete combustion, such as carbon monoxide (CO) and particulate matter (PM) (MacCarty et al., 2010). To ensure the optimisation of cookstoves for the future, the development of improved combustion science for these systems is essential (Simon et al., 2014).

It is widely known that a key attribute for complete combustion is to create sufficient mixing of oxygen with the fuel. Without adequate mixing, and the necessary feedback from the hot combustion products, emissions of incomplete combustion will remain high. Recognising the importance of mixing in the improvement of efficiency and reduction of pollutants, an increasing number of improved cookstoves seek to incorporate forced draught. Stoves that apply the assistance of blowers or fans increase the stove price dramatically, however with low-cost computer-based blowers being available now this problem can be ameliorated (Kshirsagar and Kalamkar, 2014). It has been observed that when using forced air the heat transfer to a vessel would increase, and products of incomplete combustion, foremost CO and PM, would decrease, compared to other cookstoves (MacCarty et al., 2010; Aprovecho Research Center, 2011; Kumar et al., 2013; Raman et al., 2014). The increase in the heat transfer is related to higher gas velocity of hot flue gases around the cooking vessel while the emissions reduction is believed to be caused by greater mixing of air with combustible gases. On the contrary it has also been found that forced air stoves, though more energy efficient, are not necessarily more emission efficient (Kshirsagar and Kalamkar, 2014) and although emitting relatively less $PM_{2.5}$ mass the number of ultra-fine particles can increase (Jetter et al., 2012).

There is an increasing trend for improved cookstoves to feature forced air (Kshirsagar and Kalamkar, 2014) with the widespread belief that forced air necessarily leads to greater mixing and thus increased performance. The analysis of the validity of this claim over a range of conditions is the purpose of this study. A two-stage solid fuel research furnace, analogous to a cookstove, which allows the air flow rate through a primary and a secondary inlet to be controlled was used to investigate advantages and disadvantages of forced draught in cookstoves. The measurement of emissions from the combustion and the temperatures inside the furnace enable the evaluation of the process. Especially the incorporation of secondary air, also called over-fire air, which is a key feature of gasifier type stoves could be beneficial for the presented combustion furnace.

2. Equipment and Techniques

2.1. Research Furnace

Experiments were conducted in a research furnace, shown in Figure 1, which was designed to provide control over multiple air flow rates, geometry and fuel/air locations. The furnace has an inner diameter of 206 mm and a height of 1200 mm. This size is larger than most stoves which are designed for household use, to be able to address scaling issues and to enable a greater variability of adjustable parameters. These parameters include the location and the depth or amount of the fuel, which can have an influence on the combustion process, but an investigation of these parameters is outside the scope of the present study which is focussed on the effect of the air supply. The research furnace consists of the primary air inlet chamber, the stove body, in which the fuel grate is located, and the furnace extension, as presented in Figure 1. On top of the research furnace a pot and pot-stand were added to the set-up. The pot was filled with 2L of water, and the water temperature was monitored with a K-type thermocouple. The tip of the water thermocouple was inserted through a small hole in the top of the lid of the pot to ensure that it was submersed in the water.

Figure 1: Schematic research furnace (all measurements in [mm])

The primary air (PA) flow rate can be controlled by using a small blower situated on the outside of the furnace, as shown in Figure 1. This blower is designed for the purpose of cooling personal computers. It was chosen for this application because for in-field construction of forced draught cookstoves the use of this kind of blower could achieve a far reaching impact. Personal computer blowers are readily available in many parts of the world and have previously been used for the purpose of providing forced draft in cookstoves (Anderson and Reed, 2004). The blower can be adjusted using a pulse width modulator (PWM) with five settings to adjust the primary air flow rate in relation to the maximum airflow of 14.6 L/s.

To control the global equivalence ratio of the furnace, without changing the air flow rate through the fuel bed, compressed air was injected into the furnace as secondary air (SA). The SA flow enters the furnace downstream of the fuel bed via 12 equi-spaced radial injection streams. The injection streams consist of 290 mm long pipes, with an inner diameter of 12 mm, and a 1.2 m long flexible hose. All hoses are connected to a manifold to ensure uniform flow rate through the SA injection streams. The flow rates are controlled using a rotameter situated upstream of the manifold.

2.2. Fuel

Wood chips were the fuel used for the experiments reported in this paper. These wood chips were produced from Radiata Pine (*Pinus Radiata*) trees sourced from a timber processing plant in Jamestown, South Australia. Pine bark also accounts for a small portion of the chips (less than 10%). A sample tested was found to include chips varying from $75 \times 25 \times 3$ mm to $8 \times 5 \times 2$ mm with the average size approximately $30 \times 20 \times 3$ mm. A controlled moisture content of approximately 10% was established for all experiments. Wood chips were chosen as fuel because wood is the most commonly combusted biomass (Yevich, 2003). The mass of fuel used for all tests was 1.0 kg.

2.3. Measurements

Emissions were measured using a Testo 350 Flue Gas Analyser. Measurements included oxygen (O_2), carbon monoxide (CO), and carbon dioxide (CO_2). The flue gas measurements were taken at 830 mm above the exit plane of the furnace extension, along the central axis of the furnace. All concentrations recorded are on a dry basis. Mean gas-phase temperature measurements were obtained using a K-type thermocouple mounted in location A, as shown in Figure 1 and the water temperature inside a pot was measured, as described in section 2.1.

2.4. Test Procedure for Varying Primary Air

Investigations into the effect of primary air flow rate were conducted with a furnace extension height set at 310 mm, a distance from the furnace extension to the pot of 50 mm and the secondary air flow rate set at 6.4 L/s. Tests were conducted at the primary air flow rates of 14.6 L/s, 8.8 L/s and 5.9 L/s, each repeated three times. To minimise thermal variations between tests, the furnace was pre-heated to approximately 65°C. For each experiment 1 kg of fuel was loaded onto the fuel grate. During testing the research furnace was placed under a fume extraction duct and the pot containing 2 L of water was placed above the exit plane of the furnace extension. The pot was placed onto the pot stand and visually aligned with the flue to ensure the exhaust gases flowed evenly around the outside of the pot. The temperature of the water in the pot, and the time taken to achieve water boiling, give an indication of the heat transfer from the hot gases issuing from the furnace to the pot.

To ignite the biomass, approximately 50 mL of methylated spirits (96% ethanol) was poured into the furnace over the biomass fuel. The primary air and the secondary air were turned on after one minute to the predetermined value for each experiment. The experiments were conducted for 13 minutes, with both airflows turned off after 11 minutes. The experiments were run in a continuous cycle to ensure that the furnace always started at the same temperature, being pre-heated by the previous experiment. For each set of parameters the test was repeated three times and the arithmetic mean of the results is presented. Due to the variability of stove testing more tests would be advantageous (Wang et al., 2014) but the observations were found to be repeatable, such that the trends are not affected by a bias due to the limited sample size.

2.5. Test Procedure for Varying Secondary Air

Consistent with the test procedure for varying primary air presented in section 2.4, the same procedure was used for a second set of experiments, but instead the secondary air (SA) was varied. The PA was kept constant at 14.6 L/s and the SA was adjusted. Experiments were performed at SA flow rates of 1.3 L/s, 3.8 L/s, 6.4 L/s and 9.0 L/s.

3. Results and Discussion

3.1. Varying Primary Air Flow Rate

3.1.1. Oxygen profile

Figure 2 shows the mean oxygen concentration from three independent test measurements, at each of the three various primary air (PA) flow rates. At the beginning of the burn cycle the initial concentration of oxygen (O_2) is approximately 21%, as expected. During the combustion process the O_2 concentration decreases as a function of time for all levels of PA until it reaches a minimum at approximately 350 seconds. It can be assumed that at this point, after 350 seconds, the combustion intensity is greatest, consuming the oxygen and leading to these low values. In all cases it is noted that the lowest O_2 concentration is greater than 5% (on a volumetric basis). This measurement is influenced due to the fact that the emissions were measured at 830 mm above the top of furnace extension, where they have been mixed with surrounding air. The high O_2 concentrations suggest though that with all the PA flow rates the system operates fuel-lean.

Figure 2: Mean O_2 concentrations with varying primary air

Of particular note from Figure 2 is that the oxygen concentration returns to 21% at approximately the same time for all PA flow rates. This indicates that the burn-time for all cases is approximately 650 seconds. The average air to fuel ratios ($A/F = kg_{air}/kg_{fuel}$), for the complete combustion of all fuel over the time period of 650 sec are presented in Table 1. These values are calculated assuming a molar ratio of the biomass fuel of approximately

$CH_{1.4}O_{0.6}$, as has been suggested to be an average for woods, with a resulting A/F of 6.3 for complete combustion (Saravanakumar et al., 2007). The presented calculations in Table 1 are highly simplified, since they are based on many assumptions, such as a uniform fuel consumption during the combustion process. Bearing these assumptions in mind the values in Table 1 give an indication which supports the suggestion of constantly fuel-lean conditions. In all cases, except for a primary air flow of 5.9 L/s, overall fuel-lean conditions appear to be achieved by the primary airflow.

Table 1: The primary and secondary air flow, the average air/fuel (A/F) ratio for the primary air flow as well as the overall A/F ratio for the consumption of all fuel over the whole burn-cycle of 650 s and the average nominal combustion efficiency (NCE) for all configurations.

Varying primary air flow				
Air flow		A/F ratio		NCE
Primary [L/s]	Secondary [L/s]	Primary [kg_{air}/kg_{fuel}]	Overall [kg_{air}/kg_{fuel}]	
5.9	6.4	5.1	10.6	0.919
8.8	6.4	7.6	13.2	0.916
14.6	6.4	12.7	18.2	0.944
Varying secondary air flow				
14.6	1.3	12.7	13.8	0.923
14.6	3.8	12.7	16.0	0.932
14.6	6.4	12.7	18.2	0.944
14.6	9.0	12.7	20.4	0.951

The SA is introduced downstream of the flame front, such that the primary air flow rate should control the combustion of the solid fuel. The addition of secondary air serves predominately to create mixing of air and the primary combustion products, and is aimed to lead to the complete combustion.

3.1.2. The nominal combustion efficiency

Figure 3 presents the nominal combustion efficiency (NCE), the relation of CO_2 emissions normalised by the sum of CO and CO_2 emissions (Jetter et al., 2012), for varying primary air flows. This normalisation procedure was performed because the emissions were measured at a position of 830 mm above the furnace where they have been mixed with surrounding air. Due to this mixing effect the measured concentrations have been diluted and could be misleading. The NCE provides a relation of the carbonaceous emissions of complete combustion, CO_2, to the intensity of the combustion process, represented by the sum of all measured carbonaceous emissions, CO and CO_2. This normalisation is independent of location of the measurement and therefore allows an evaluation of the combustion process. High NCE values, which can be seen in the first part of the process up to approximately 450 seconds, represent a high combustion performance and low emissions of incomplete combustion. The rapid fall of all curves after the initially steadily high values is assumed to be due to the transition from primarily volatile combustion to primarily char combustion (Jones et al., 2014). In the second part of the process mainly charcoal remains as fuel, which usually accounts for about 20 - 30% of the initial mass (Huangfu et al., 2014). The produced charcoal has a highly porous structure and it consists primarily of carbon. The carbon reacts with oxygen on its surface, largely inside the porous structure (Emmons and Atreya, 1982). This surface oxidation causes high emissions of CO which can subsequently oxidise further to form CO_2 if sufficiently high temperatures and oxygen are available (Glassman et al., 2015). Although with all three primary air flows sufficient oxygen is supplied for complete combustion, as shown in Section 3.1.1, the CO emissions are high in the char combustion phase. Table 1 presents the average NCE over the burn-time for the respective tests, which shows that the NCE value increases only by 2.5% with a 2.5 times greater primary air/fuel ratio. This shows that by only increasing the primary air flow no drastic reduction of emissions of incomplete combustion can be achieved. In the first two cases, of 5.9 and 8.8 L/s PA, the average NCE is similar to the average of an open fire during a day of in-home use (Johnson et al., 2010). This lead to the choice of 14.6 L/s of primary air for the tests of varying secondary air, as the goal is to achieve a NCE as high as possible.

Figure 3: NCE values for varying primary air

3.2. Varying Secondary Air Flow Rate

3.2.1. Carbonaceous emissions

Figure 4 presents the NCE profiles from varying SA flow rates. It shows that the NCE, similar to the profiles of varying PA, is relatively high in the first part and low in the second part of the burn-cycle. In the beginning, predominantly combustion of volatile compounds, that are released from the fuel stack, is taking place. The consistently high NCE shows that a variation in SA air flow does not have an influence on this part of the combustion process. Towards the end, when most of the volatiles from the fuel are combusted, char remains. The NCE falls during the char combustion, which occurs after the peak intensity of combustion (∼350 seconds, as mentioned in section 3.1.1). The CO levels are highest for the lowest secondary air flow rate of 1.3 L/s SA.

Figure 4: NCE values for varying secondary air

When char combustion occurs in the fuel bed, the oxidation process could be assumed to be controlled by the primary air flow rate rather than the secondary air. This is reflected in the 3.8, 6.4 and 9.0 L/s SA cases, which all show similar profiles. Table 1 shows that the average NCE increases with a higher SA airflow. This indicates that there is a relationship between the SA and the fuel bed. It is hypothesised that at the higher SA flow rates some of the air is directed downward onto the fuel bed, assisting in the char combustion and thus reducing the CO emissions.

3.2.2. Flue gas temperature and heat transfer profile

Figure 5 shows in part (a) the gas phase temperature in the furnace extension and in part (b) the water temperature inside the pot for the four SA flow rates considered. It can be seen in Figure 5 (a) that when the secondary air flow rate of 1.3 L/s was used, the flue temperature was considerably higher, up to 200°C greater than at 9.0 L/s SA. The lower temperature with the higher SA flow rates does not indicate lower heat output, but that the heat is diluted by the additional air (thus lowering the temperature). Depending on the application, the additional air (thus increased gas velocity) may be advantageous, whilst other applications may require the higher temperature. The average of the water temperature, as presented in Figure 5 (b), reaches boiling point at 1.3 L/s SA (100°C) approximately 200 seconds before the measurements at 9 L/s SA. This shows that at 1.3 L/s SA flow, with the highest flue gas temperatures, the heat transfer is greatest in this combustion system.

Figure 5: (a) The Gas temperatures in the furnace extensions and (b) the water temperatures during varying secondary air tests

3.3. Discussion

In Figure 3 and Figure 4 it can be seen that in all cases the emissions of incomplete combustion are low in the first part of the combustion process and high in the second part. The first part of the process appears to be influenced by the variation of neither PA nor by SA. The volatile compounds which are released from the fuel are burned cleanly. The combustion in the second part of the process is, opposite to the first part, influenced by both PA and SA flow. With an increase of PA flow the NCE also increases, as can be seen in Figure 3, and the lowest SA flow displays the lowest NCE in Table 1. These emissions profiles need to be related to the information that the heat transfer to the pot, presented in section 3.2.2, is significantly greater with lower secondary air. This finding is in agreement with previously reported lower heat transfer with higher air flows in a biomass combustion furnace (Selim et al., 2011). Therefore a trade-off needs to be considered between a higher NCE and lower heat transfer with a greater air flow against a higher heat transfer and lower NCE with a lower air flow.

4. Conclusions

The present study was performed on a two-stage research furnace to investigate the influence of the application of primary as well as secondary air on the combustion process of cookstoves. Two sets of experiments were performed. In one set the secondary air (SA) was held constant while the primary air (PA) was varied. In another set the PA was held constant while the SA was varied. This allowed the influence of air flows over a range of conditions to be studied.

The results show that the first part of the combustion process, where the combustion of volatile compounds prevails, exhibits similar emissions profiles for all air flow applications, with low emissions of incomplete combustion. In the second part of the process, where mostly char combustion is taking place, higher primary air (PA) flows cause a higher nominal combustion efficiency (NCE), but even an excessive supply of air does not lead to a significant reduction of products of incomplete combustion. Furthermore although an increase in SA supply steadily raises the NCE it has to be considered that it also lowers the heat transfer to a pot on the stove.

Thus it has been shown that both forced primary air and forced secondary air do have an influence on the stove performance. The increase of PA and laterally introduced SA aid in the mixing of fuel and air and lower the emissions of products of incomplete combustion, but also they cause a lower heat transfer. Therefore the application of forced draught for primary air as well as secondary air should be further investigated to achieve greater mixing and higher NCE values without increasing the amount of air, introduced into the system. Also it should be considered that different air flow rates in the first and second part of the combustion process could be advantageous.

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