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Research paper

Natural draft and forced primary air combustion properties of a top-lit up-draft research furnace

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ABSTRACT

Worldwide, over four million people die each year due to emissions from cookstoves. To address this problem, advanced cookstoves are being developed, with one system, called a top-lit up-draft (TLUD) gasifier stove, showing particular potential in reducing the production of harmful emissions. A novel research furnace analogy of a TLUD gasifier stove has been designed to study the TLUD combustion process. A commissioning procedure was established under natural draft and forced primary air conditions. A visual assessment was performed and the temperature and emissions profiles were recorded to identify the combustion phases. The efficiency was evaluated through the nominal combustion efficiency (NCE = $CO_2/(CO_2 + CO)$), which is very high in the migrating pyrolysis phase, averaging 0.9965 for the natural draft case. Forced primary air flows yield similar efficiencies. In the lighting phase and char gasification phase the NCE falls to 0.8404 and 0.6572 respectively in the natural draft case. When providing forced primary air flows, higher NCE values are achieved with higher air flows in the lighting phase, while with lower air flows in the char gasification phase. In the natural draft case high H_2 emissions are also found in the lighting and char gasification phases, the latter indicating incomplete pyrolysis. From the comparison of the natural draft with the forced draft configurations, it is evident that high efficiency and low emissions of incomplete combustion can only be achieved with high controllability of the air flow in the different phases of combustion.

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1. Introduction

Energy consumption in private households in developing countries is still primarily based on biomass fuels. This directly affects 2.7 billion people [1] who rely on traditional cooking methods, which typically have a very low efficiency and produce harmful emissions through incomplete combustion. This results in approximately 4.3 million premature deaths worldwide each year from cooking-related illnesses caused by household air pollution [2]. In order to achieve substantial health benefits, cleaner burning cookstoves than are currently in widespread use are needed [3,4]. One type of cookstove that has been recognised as potentially able to achieve this goal are "gasifier" stoves [5]. These stoves force volatile gases out of a solid fuel and burn them separately from the solid body [6]. This can reduce harmful emission production; however, there is a lack of scientific understanding to enable stove optimisation.

Gasifier cookstoves can be distinguished by the direction of the gasification air. Available designs of cookstoves use either updraft, downdraft or inverted downdraft, also called top-lit up-draft (TLUD), flow [7]. A TLUD stove is investigated in this study. To operate as a TLUD, the stove is filled with batches of fuel and lit from the top. Firstly, the top layer of biomass is ignited, typically by a kindling material, before a pyrolytic front forms, which moves downwards, opposite to the gas flow, through the fuel-stack, as illustrated in Fig. 1. In the enclosed space of the stove, the oxygen is quickly consumed in the oxidation process of the lighting phase. The heat released from the top layer causes lower layers to pyrolyse, which means that volatile matter is released from the fuel in an inert atmosphere [8]. This process is called a migrating pyrolytic front [9], which moves, in relation to the primary air, down the fuel-stack [10]. The pyrolysis products are liquids (water, heavier hydrocarbons, and tars), gases (such as CO, CO_2, or CH_4) and solid char [11]. The pyrolytic front is sustained by simultaneous gasification, in which the pyrolysis products can partially oxidise with the primary air into gases (CO, CO_2, H_2 and lesser quantities of

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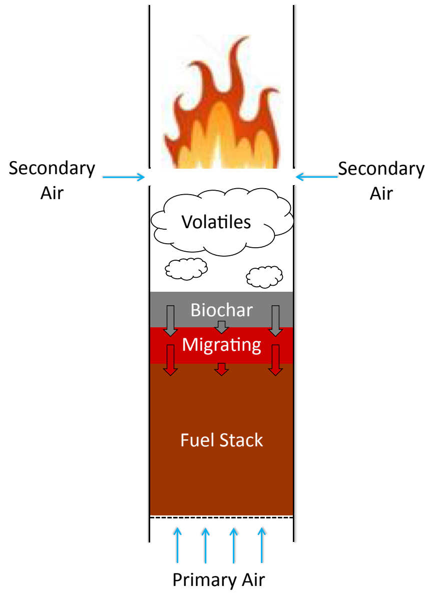

Fig. 1. Schematic diagram of TLUD operation.

hydrocarbon gases) [12]. In inverted downdraft gasifiers, heavier hydrocarbons and the liquid tar can crack into lighter components as they move through the high temperature zone of the char layer [10,13]. This process is highly complex, in part due to the thin char layer [14], and therefore the scientific understanding of these reactions in TLUD stoves is limited. Greater scientific understanding of the tar cracking processes for TLUD stoves is needed to ensure optimisation of systems in terms of emissions production.

The combustible pyrolysis products leave the fuel-stack at temperatures of $\approx 600\ ^\circ C$ [15], and are mainly composed of CO, H_2, CH_4 and some heavier hydrocarbons (C_xH_y) [16]. Once these gases reach the secondary air inlet, they are mixed with air and can be combusted if an ignition source is present, as shown in Fig. 1. As a result of gas-combustion and compared with other cookstoves, gasifier stoves have been shown to produce low CO and particulate matter (PM) emissions under laboratory conditions [17,18]. It has been shown that variations in the stove geometry and the utilized fuel have a significant impact on the stove's performance [19,20]. It has been observed that the heat transfer, to a vessel on the stove, is a strong function of the vessel diameter, while swirl of secondary air has a negligible impact [14]. It is clear that the design of the stove to optimise gas production for combustion, and for subsequent heat transfer are limited.

From the pyrolysis processes, char remains as a solid product. The char yield is mainly dependent on the superficial velocity, which is determined by the gas flow over the cross-sectional area [10] and the moisture content of the biomass [21,22]. This char can be further gasified and combusted in the stove or, if no further air is supplied and the oxidation process is quenched, it can be collected. If collected, the char can be used as either fuel or as a soil amendment (termed biochar). When using it as a soil amendment, the whole process could be seen as a mechanism for carbon sequestration [19,23]. If the quenching process is not conducted early enough, the char can continue to burn, producing high levels of harmful emissions, as well as produce ash, which cannot be used as a solid enhancer. It is therefore necessary to further develop the understanding of quenching of char for subsequent use, or for improved combustion in a process beneficial to the end user.

Uncertainty in the existing results is exacerbated by the influence of different standardised tests and kindling materials on the performance of TLUD cookstoves. Arora et al. assessed different test protocols, and determined that, for given conditions, the emissions factors, (primarily of CO and PM), varied leading to differences in the cookstove performance. Wood, mustard stalks and kerosene were tested as kindling materials and it was observed that CO peaks would increase with lower calorific values of the kindling materials [24]. All of these studies have evaluated specific designs and analysed their performance while performing cooking tasks.

The previous paragraphs show that there are many gaps in scientific understanding of basic TLUD operation and design. These unknowns are extended when considering various fuel types and fuel quantities. Additionally, it is also known that these stoves can be used under natural draft conditions or with the assistance of a fan that creates a forced airflow. Altering the available flow rates can be beneficial, or detrimental, to the combustion processes. How these modifications influence the heat transfer, emissions production and burn rates are all crucial in development improved cookstoves and thus helping increase the quality of life for billions of people. However, much of the research has been conducted on stoves that do not allow for modification of these aspects. It is for this reason that a TLUD analogous furnace has been developed to allow for systematic studies of TLUD combustion. What is not completely known is how accurate the analogy is across all aspects of TLUD stove design.

The aim of the current paper is to present results from commissioning a TLUD analogy furnace and determine if forced draft flows can be used to simulate natural draft. Specifically, the study includes analysis of emissions and temperature profiles in natural draft as well as forced primary air TLUD operation, in order to characterise, understand and evaluate subsequent combustion processes.

2. Materials and methods

The research furnace, previously presented in Kirch et al. [25], was revised as a TLUD stove with the general characteristics of a primary air inlet at the bottom of the furnace, and a lateral secondary air inlet in the upper region. The furnace's dimensions were chosen to be larger than most extant commercial products and stoves in order to address scaling issues and achieve greater variability of the adjustable parameters. The furnace enables various combustion-relevant parameters to be controlled. The increased size of the research furnace allows the amount and location of the fuel to be widely altered which in turn permits the scaling from use in private households to use in communal kitchens to be studied, although this is outside the scope of the present study. The principal components of the research furnace are a stove body, a primary air inlet chamber and a secondary air inlet stove extension, which are shown in Fig. 2.

2.1. The TLUD research furnace

The central component of the research furnace is a 600-mm-tall steel cylinder with an inner diameter of 206 mm and 8 mm wall thickness, illustrated in Fig. 2. Inside the stove body, a grate is located, which holds the fuel-stack in place. The circular grate is perforated with 3-mm-diameter holes, with 26% open-area ratio. This allows air from beneath the grate to enter the fuel-stack. The fuel grate is located 420 mm below the top of the stove body and is easily removable for post-combustion analysis of the solid residual matter, as well as cleaning. The steel cylinder, in combination with the fuel grate, forms the stove body. It is placed on top of a steel frame that serves as the primary air inlet chamber.

The steel frame of the primary air inlet chamber has the following dimensions: 248 mm $\times$ 248 mm $\times$ 150 mm

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