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Investigation of Lignite and Firewood Co-combustion in a Furnace for Tobacco Curing Application

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Abstract: Co-combustion of lignite and firewood was investigated for an application in tobacco curing industry in Northern Thailand. Extensive experiments have been carried out in a newly developed furnace suitable for small curing unit, in place of locally made furnace. The aim of this investigation is to evaluate the performance of the combustion chamber in the required thermal output range for tobacco curing and to examine the influence of fuel feed rate, fuel mixture ratio and air staging on the combustion and emission characteristics of the furnace during steady state operation. Their effects are characterized in terms of the observed variations of temperature distributions, emissions of CO, SO_2, CO_2, O_2 and combustion efficiency. Co-firing of firewood and lignite has been found to exhibit acceptable temperature distribution, high combustion efficiency and low emissions over a wide thermal output span. Stable operation at low (50 kW) and high (150 kW) thermal output was achieved with average CO and SO_2 content in flue gas typically below 1400 and 100 ppm, respectively. Under the conditions considered, it was showed that the fuel feed rate had greater influence on combustion and emissions than firewood and lignite mixture ratio and air staging.

Key words: Co-firing, biomass, fixed bed, emissions, bulk curing

INTRODUCTION

Tobacco production and curing practice is among the most important agro-industry in Northern Thailand, involving several 10,000s of farmers. During the past several years, the production is approximately 20 million tons of dried tobacco a year. Traditionally, tobacco crop is flue-cured by individual farmer in the field. Traditional method is based on natural convection where fresh tobacco is hung loosely inside a curing barn and heat is provided from a hot flue pipe connected to a locally made furnace. Its thermal efficiency was reported to be very poor, being around 10 – 15% or even less[1–4]. It is apparent that energy used represents a major fraction in tobacco production cost.

Thailand's flue curing tobacco barns are mostly of traditional type with no standard dimensions for the size of a barn. The most commonly used barns have floor areas of about 6 x 6 m^2, with a loading capacity of about 3,000 – 6,000 kg of fresh tobacco leaves per curing batch, depending upon sequence of leaf picking. Thermal power in the range between 20-150 kW is typically required for each curing step[5]. In general, curing of Virginia tobacco is classified into four steps, involving a coloring process, a color fixing process, a leaf drying process and a stem drying process. Combustion of solid fuels on a grate in a locally made furnace is typically used. The furnace is usually made of bricks and is partly protruding inside the barn. The furnace has varying dimensions but is normally small in overall combustion volume. The flue gases are circulated through a long, 300 mm in diameter flue pipe, made of galvanized iron sheet and lay near the floor and out to stack above the barn. Traditionally, firewood is used as fuel for tobacco curing, a highly energy-intensive process which consumes enormous quantities of firewood with serious ecological implications. It was estimated that more than 200,000 tons of firewood is used in this industry in Thailand each year, contributing significantly to the severe deforestation problem. Fuel switching to lignite or partial substitution with lignite is widely adopted. However, the practice is not welcomed in many areas due to its odor and emitted air pollution. A poor furnace design in traditional curing barn appears to be one of many aspects at the root of energy efficiency and emission problems associated with traditional tobacco curing practice. In recent years, co-combustion of a fossil based fuel such as lignite, with an alternative fuel like firewood or waste wood has been increasingly recognized as an effective means to increase the use of renewable energy source and in reductions of pollutant emissions associated with burning of the fossil fuel[6]. The approach is particularly attractive if the fossil fuel contains high sulfur content as co-combustion with biomass improves sulfur retention and reduces SO_2 emissions substantially.

Tobacco curing is one of the biggest consumers of firewood and lignite among the agro-industrial

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processes in Northern Thailand. Experimental results from previous studies underline the urgent need to improve traditional tobacco curing practice[1, 2, 5, 7]. One way to improve efficiency of the curing process is to improve the furnace and flue pipe system design. A large central boiler requires exceedingly high initial investment, preventing individual farmers to adopt it. It is apparent that investigation into a cheaper, yet effective furnace system to reduce energy consumption in traditional tobacco curing practice for small individual farmers is urgently needed. A newly designed fixed bed furnace suitable for small tobacco curing barn, developed by Department of Mechanical Engineering, Chiang Mai University and shown in Fig. 1, is an improvement from existing combustion chamber design with appropriate technology. The combustion chamber is designed for a maximum heat load of about 150 kW, capable of using a wide range of fuels, including crushed lignite, firewood and dried agricultural residues. The design concepts are centered on the following aspects; low overall cost, wide range of fuel, minimum fuel processing and ease of use and maintenance so as to be attractive for local farmers. It should also be able to reduce the level of pollutants and to improve the quality of bottom ash. The design is relatively novel for local tobacco farmers and the market for this type of installation is expected to expand substantially in the near future. The objective of this experiment is to evaluate the performance of the furnace at constant thermal output. Combustion and emission characteristics of lignite/firewood co-firing are investigated in terms of variations of temperature distributions, emissions of CO, CO_2, SO_2, and O_2. Combustion efficiency is evaluated via the emission of CO and carbon conversion of the fuel.

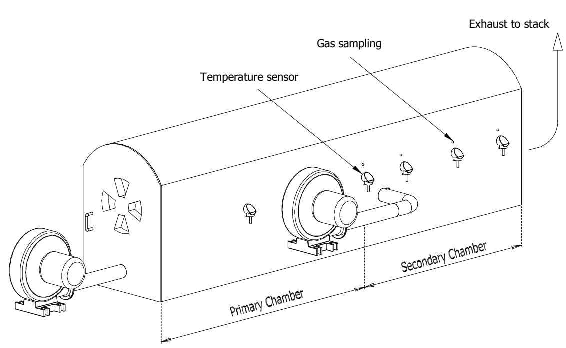

Fig 1: Schematics of the furnace and experimental setup

MATERIALS AND METHODS

Fuels: Air dried firewood with moisture content less than 5% has been used during the experiments with low sulfur crushed coal (S ≅ 1.0% d.a.f.) from Ban Pu mine, Chiang Mai. The same batch of fuels was obtained and used to avoid variation in fuel properties, as supplied by local fuel distributors. Usually, firewood is supplied as logwood and stocked over a few months prior to their usage. The size of fuels used can be classified as large with typical size between 20-100 mm for lignite and about 50 mm in diameter and 0.4 m long for firewood. Results of their property analysis are shown in Table 1.

Table 1: Proximate analysis and heating value of fuels used

Fuel (*wt% as received*)	Lignite	Firewood
Moisture	4.5	1.5
Volatile	43.5	79.4
Fixed carbon	44.8	16.6
Ash	7.2	2.5
Heating value (MJ/kg)	24.5	19.0

Furnace: Experiments were conducted in a fixed bed furnace depicted in Fig. 1. The furnace was designed in such a way that (i) it has large volume to ensure a sufficient gas residence time of at least two seconds for combustion at maximum thermal output, (ii) it was fully insulated to ensure higher temperature inside the furnace due to low heat loss through walls, (iii) it enables better mixing of fuel and air, and has good air distribution under the grate[8]. It should also be able to utilize a wide range of fuel types and have a wide thermal output range suitable for curing with acceptable response for heat load variation. The furnace is about 3.0 m long, thermally insulated by a 120-mm refractory wall, forming primary and secondary chambers in succession. Its cross section area above a grate is 0.4 x 0.6 m^2. Fuel feeding has been done manually at an interval of 30 minutes. Fresh fuels enter at the front opening of the furnace and are pushed inwards the primary combustion chamber so that these fuels are dried before combustion starts using heat transfer by radiation and convection from the burning gases. Devolatilization and char combustion takes place towards the end of the primary chamber. Combustion air was provided via a blower. A grate was installed in the primary chamber to distribute air uniformly under the fuel bed and to allow simple ash collection with an access through the front gate at the bottom. The burned as well as combustible gases from the primary chamber flow to the secondary chamber where preheated secondary air is supplied by means of a blower and a 2-kW air heater. Gases leave the furnace through flue pipe system and exhaust to stack.

Experimental setup: The experimental test facilities are accommodated in a farm near Sankampaeng, Chiang Mai. The facilities include the furnace and heat transfer unit, a flue pipe system, air circulation system and a curing barn. Analysis of temperature and gas composition is carried out along the axial length of the secondary chamber near the centerline at 0.30 m above the grate. Type K thermocouples were used to measure temperature with an accuracy of 0.1°C and a response time of about 1 s. CO, CO_2, SO_2 and O_2 in the flue gas were measured using a Testo 350XL multi-component flue gas analyzer. Airflow rates were regulated by means of a calibrated volume flow meter. Thirteen different conditions have been experimentally studied in which the fuel feed rate, the coal/biomass mixture ratio, the secondary air to total air flow ratio and the secondary air temperature have been used as parameters. Co-combustion at fuel feed rate of 10 – 30 kg/hr corresponding to approximately 50 to 150 kW thermal output and lignite/firewood mixture ratio in terms of percentage firewood fraction of 0, 25, 50 and 100% firewood were performed at a fixed excess air of around 100%. Secondary air to total airflow rate and preheat air temperature were varied in the range of 0, 10, 20 30% and 30, 50, 100°C, respectively. All measurements were taken when steady state was reached for each condition at intervals of about five minutes throughout the test runs. Combustion efficiency is calculated from the ratio of CO_2 to the sum of CO and CO_2 in burned gases, as in Jangsawang and Kerdsuwan's work[9].

RESULTS AND DISCUSSION

Temperature distribution: Gas temperature distribution along the length of the furnace is shown in Figs. 2 to 4 as a function of fuel feed rate (FR), lignite/firewood mixture fraction (%firewood) and secondary to total air ratio (SA). The position, x = axial distance, where the grate ends is designated to $x = 0.0$ which is the end of the primary combustion chamber or the start of the secondary chamber. At $x = -0.4$ m, it represents a position in the primary chamber. It was found that higher fuel feed rate resulted in higher temperature distribution due to higher heating rate in the primary chamber. Temperature of the hot gas appeared to decrease gradually in the secondary chamber as a result of convective and radiation heat loss and level off towards the exit due to good insulation property of the firebrick before exhaust to the flue pipe. Similar trends were also observed for different mixture of fuel type and secondary to total air ratio. It should be noted that temperature in the combustion chamber was not very high which may be due to high excess air level used. It can be seen from Fig. 3 that the primary chamber temperature decreases with increasing fraction of firewood in lignite/firewood mixture due to lower heating value of the fuel mixture. Moisture content was not expected to play a major role here because of its low content in each fuel type used. In the secondary chamber, temperature was found to be slightly higher for co-combustion than solely lignite. This may be due to slower release rate and higher content of volatile from firewood and its subsequent combustion downstream of the grate. With respect to secondary air injection, it was found to have a weak effect on temperature distribution pattern. For a fixed total air, increase in proportion of secondary air brought about a decrease in excess air in the primary chamber which in turn resulted in an increase in the primary chamber temperature due to less convective heat loss and higher residence time, as shown in Fig. 4.

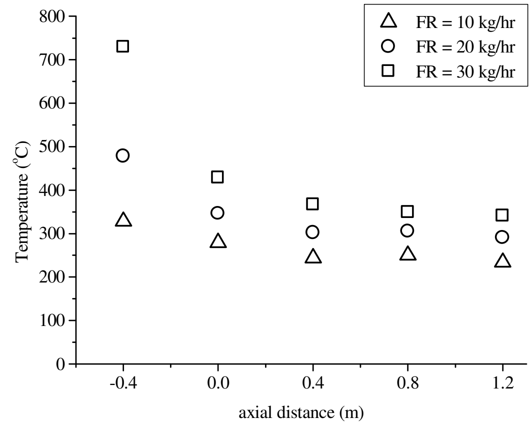

Fig. 2: Effect of fuel feed rate on temperature distribution in the furnace for 100% lignite with secondary to total air ratio = 30%

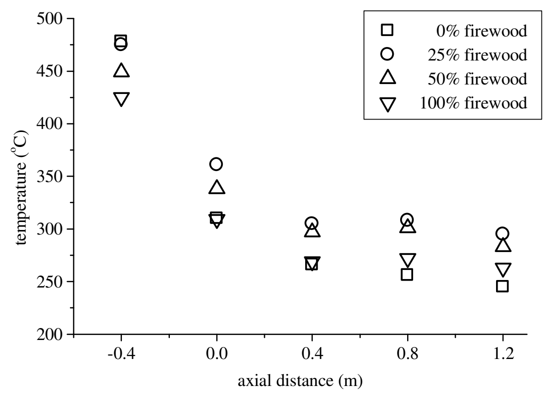

Fig. 3: Effect of firewood mass fraction on temperature distribution at fuel feed rate = 20 kg/hr with secondary to total air ratio = 30%

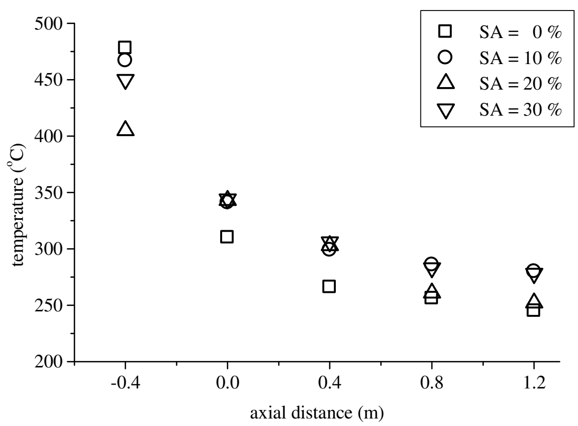

Fig. 4: Effect of secondary to total air ratio on temperature distribution at fuel feed rate = 20 kg/hr for 100% lignite

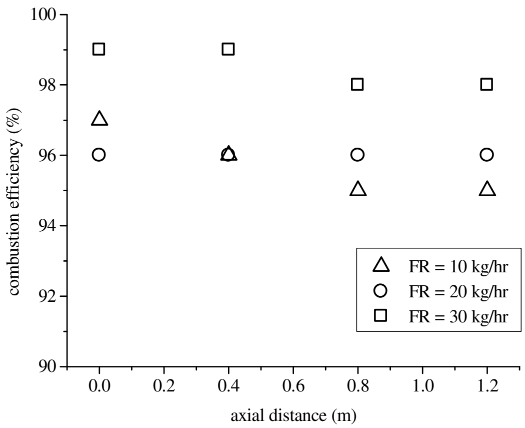

Fig. 5: Effect of fuel feed rate on combustion efficiency in the furnace for 100% lignite with secondary to total air ratio = 30%

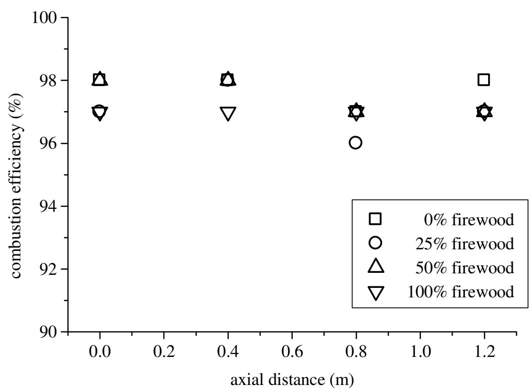

Fig. 6: Effect of firewood mass fraction on combustion efficiency at fuel feed rate = 20 kg/hr with secondary to total air ratio = 30%

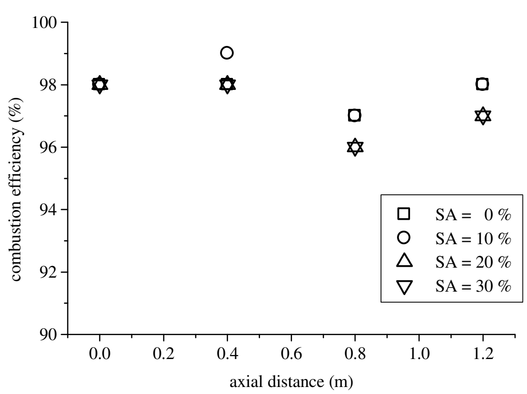

Fig. 7: Effect of secondary to total air ratio on combustion efficiency at fuel feed rate = 20 kg/hr for 100% lignite

Combustion efficiency: Figures 5 to 7 show the effect of fuel feed rate, lignite/firewood mixture fraction and secondary to total air ratio on combustion efficiency along the secondary combustion chamber. Generally, imperfect air distribution and locally inadequate combustion air as well as low combustion temperature due to radiation loss would lead to incomplete oxidation for fixed bed combustion[10]. In this investigation, combustion efficiency was found to be high for all cases, above 95% and did not vary significantly with axial distance. In Fig. 5, increase in fuel feed rate from 10 kg/hr to 30 kg/hr resulted in a jump of combustion efficiency to almost 99%. This was a direct outcome of higher temperature and heating rate in the combustion chamber. It was anticipated that combustion efficiency would decrease with increasing firewood mass fraction because of lower overall heating value and higher moisture content, but it was not the case here. Distinction cannot be made from the results obtained in Fig. 6. There were two compensating mechanisms that appeared to be equally important; fixed carbon combustion and volatile combustion. With increasing firewood fraction, fixed carbon content was reduced but volatile content increased. It might have been likely that similar fuel C conversion to CO_2 occurred for each case, taking into account carbon conversion from both fixed carbon and volatile combustion. The influence of secondary to total air ratio proved to be small. Secondary air injection was not found to promote further combustion in the secondary chamber when injected air temperature was low (with the current air heater used, only up to 100^{o}C preheat temperature can be achieved) and the primary chamber operated at air-fuel-ratio well above stoichiometry.

Gas concentration: Variation of CO and SO_2 concentrations measured at the ends of the primary and secondary chamber with fuel feed rate, lignite/firewood mixture fraction and secondary to total air ratio are depicted in Figs. 8 to 10, where solid and open symbols represent values at the primary and secondary chamber, respectively. In general, gaseous concentrations were not found to vary greatly between the front and the back of the secondary chamber. High excess air level may cool the combustion zone below the temperature required to completely burn out gaseous emissions released from the fuels. Similar findings were also found for CO_2 and O_2. With regards to the effect of fuel feed rate, CO was found to be relative high at low fuel feed rate and drop markedly with an increase in fuel feed rate, hence heating rate in the combustion chamber. It was likely that distribution of the air flow through the fuel bed may not be uniform, leading to local fuel-rich pockets that gave rise to incomplete combustion. At higher flow rate, distribution may be better as a result of higher turbulence intensity. Meanwhile, SO_2 appeared to increase as the fuel feed rate increased. This was expected because of an increase in sulfur mass rate together with greater degree of burning rate. Replacing a fraction of lignite with firewood did not appear to affect CO but reduce SO_2

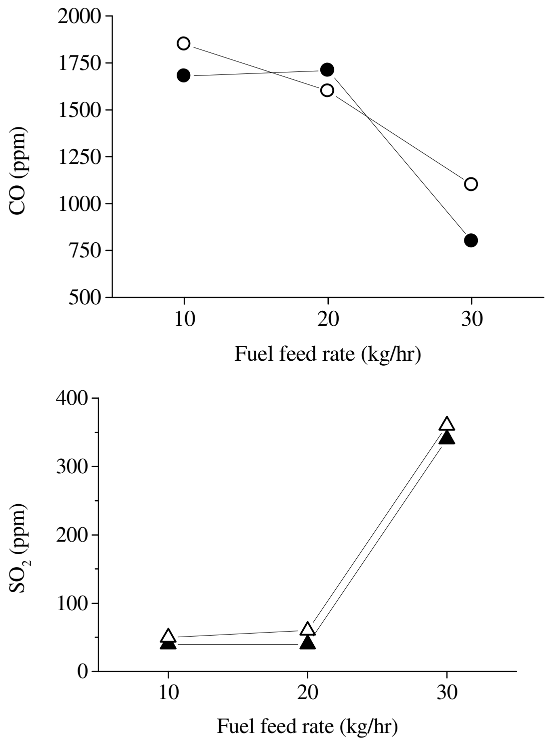

Fig. 8: Effect of fuel feed rate on flue gas concentration in the furnace for 100% lignite with secondary to total air ratio = 30% (solid symbol - primary chamber and open symbol - secondary chamber)

concentration. This was mainly due to dilution effect since firewood has negligible sulfur content. Additional possible explanation was that calcium content in ash of biomass can act as an active sulfur capturing agent[6]. However, in this investigation, Ca content in ash has not been determined. It was inconclusive that SO_2 retention by this mechanism is important in this case. From Fig. 10, secondary air injection did not appear to have strong effect on CO concentration. Only a marginal change in CO was caused by an increase in secondary to total air ratio. Meanwhile, noticeable influence was observed for SO_2 concentration. SO_2 was found to increase as SA ratio increased up to 20%. This may be attributed to the fact that an increase in proportion of secondary air resulted directly in the reduction of excess air in the primary chamber. Decreasing excess air in the primary chamber brings about a lower O_2 concentration, higher gas temperature and lower degree in gas-solid contact which promoted greater SO_2 emissions. The results were in qualitative agreement with Suksankraisorn *et al*[6]. The cause of a sharp drop in SO_2 when increased SA further to 30% is not yet clear.

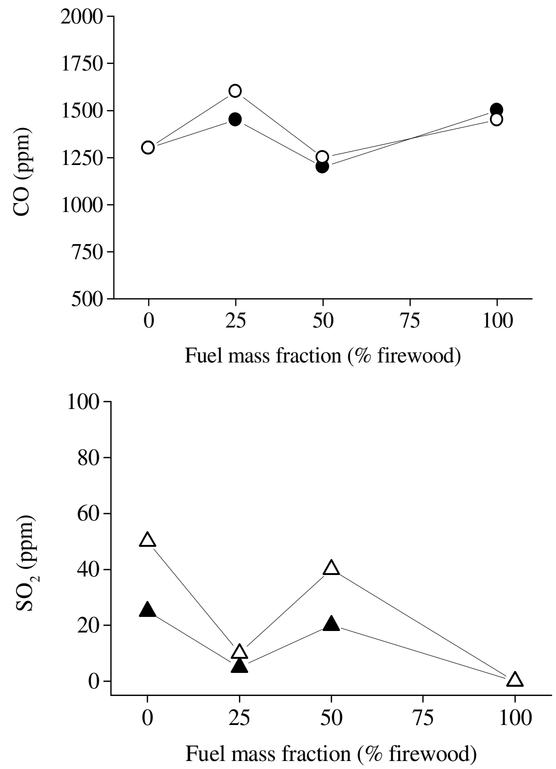

Fig. 9: Effect of firewood mass fraction on flue gas concentration at fuel feed rate = 20 kg/hr with secondary to total air ratio = 30%

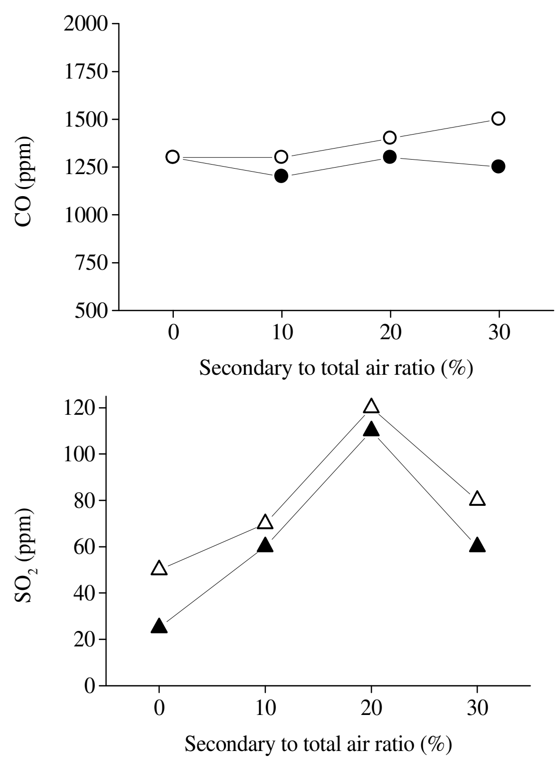

Fig. 10: Effect of secondary to total air ratio on flue gas concentration at fuel feed rate = 20 kg/hr for 100% lignite

Fuel burnout: Limited analysis of the amount of unburnt carbon in ash and solid residue under the grate has been performed. The results indicated that the amount of unburnt carbon in ash was high, about 7.5% of dry substance, in comparison with results from literature[11, 12]. It has been observed that char and solid fuel aggregates may fall from the fuel bed through the grate and mixed with bottom ash, giving rise to an increased amount of unburnt carbon, especially during ash removal and fuel feeding.

CONCLUSION

Experiments to investigate operation and co-combustion of air-dried firewood and low sulfur lignite in the new furnace for tobacco curing have been performed. Effects of fuel feed rate, fuel mixture fraction and secondary to total air ratio were also studied in terms of temperature distribution, combustion efficiency and emissions of CO and SO_2. It was demonstrated that the new furnace could be operated successfully at low emissions in the required range of thermal output for tobacco curing. At small thermal output or fuel feed rate, combustion intensity was low, resulting in low gas temperature and relatively high CO emission. Within the ranges of experimental conditions considered, as fuel feed rate increases, combustion and emissions improve. Co-combustion of lignite and firewood did not seem to significantly affect the combustion process. On average, fluctuation less than 5% was observed for combustion efficiency and CO concentration. Slight improvement in SO_2 was obtained from co-firing, mainly due to the dilution effect. Proportion of secondary to total airflow did not show strong influence on combustion and CO emission. Small incremental change was observed for hot gas temperature and CO concentration but SO_2 emission was affected by secondary air injection when excess air level in the primary chamber was altered.

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