Residual biomass gasification on a small scale and its thermal utilization for coffee drying

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Abstract

The tradition in Colombia of processing coffee in each farm provides a source of residual biomass (coffee pulp) with a potential for transformation into synthesis gas through the process of biomass gasification, since 40% of the weight of the harvested coffee is fresh pulp. The conceptual design, construction and commissioning of a downstream biomass gasifier was carried out with the aim of using coffee pulp as the source of biomass as it is readily available on all coffee farms. During the operation of the gasifier, the process gives rise to a combustible gas and biochar. The latter can be used for soil amelioration, in the coffee plantation, as well as being a means of sequestering atmospheric carbon. After the process of mechanical separation, the coffee pulp was submitted to solar drying after which it presented a uniform particle size, between 2 and 3 mm, ideal for use in fixed bed gasifiers. In this study, the coffee pulp was compared with two other sources of biomass; rice hulls and “cisco” (the outer skin of the coffee bean available from coffee processing factories. While the gasifier operates, the fuel gas is thermally harnessed through a heat exchanger, which heats the air stream to a constant temperature of 50 Â°C. The hot air is supplied to a traditional coffee dryer, where the coffee grains are dried to 12% humidity for further packaging and marketing.

It was evident during the tests that the gasifier needed a stabilization time to obtain a stream of stable and combustible synthesis gas. The dried coffee pulp produced a synthesis gas of more uniform quality as compared with the rice husks and the coffee husks. The time to stabilise the gas flow and the rate of consumption of biomass also favoured the use of coffee pulp compared with the other feedstocks. By contrast, the relative production rate of biochar was higher for rice husk compared with coffee pulp and cisco” which did not differ. The quality of the biochar, as indicated by its capacity to absorb water was also highest for the rice husk biochar. The coffee pulp was associated with a minimum degree of obstruction of the pipes by tar, in contrast to the coffee husks that produced more tar. Biochar contamination of the synthesis gas stream was also apparent when the fuel was rice husks or coffee husks due to their lower density compared to the coffee pulp.

Key words: *biochar, by-products, downdraft gasifier, renewable energy, syngas*

Introduction

According to the United Nations Development Program, Colombia is a country that is especially vulnerable to climate change, because of the location of its population in the floodplain areas of the coasts and in the unstable soils of the higher parts of the mountain ranges. Traditionally Colombia has been a country of agricultural vocation and exploitation of natural resources. For more than 50 years, coffee growing has been the main means of subsistence for more than 560,000 farmer families. However, small-scale producers remain vulnerable to an international market for volatile commodities and the unpredictable effects of climate change.

The energy requirement for the production and transformation of coffee has been a traditional challenge to boost development in this productive sector of the country. The drying of the bean is the most important, since it determines the quality of the product by preventing damage caused by fungal attack; it is this stage that influences the selling price as market requirements are for a moisture content of between 10 and 11%.

In Colombia, the annual harvest period is between the months of April-May and October-November. However, in most coffee areas the harvest overlaps with periods of rain thus hindering traditional solar drying in open courtyards or under plastic canopies. This has led to the implementation of mechanical drying techniques, using controlled temperature silos, which accelerates the drying process. These silos must operate with temperatures between 48 and 52Â°C. Higher temperatures can affect the organoleptic properties of the coffee and therefore its value (Rodriguez and Zambrano 2011). The heat used in the silos generally comes from the combustion of biomass such as rice husks, firewood, maize cobs, coffee husks, and frequently hydrocarbons such as LPG or diesel. However, even though in some cases the fuel is waste from other agricultural processes, their collection and transportation increase the costs of coffee production and are mostly not available to the average producer.

The wet processing of coffee in the farm generates solid and liquid by-products. The liquid fraction is composed of mucilage and wash-water, which can be used as animal feed. The solid fraction is composed of the outer skin also known as coffee pulp and represents about 44% of the weight of the fresh coffee cherry (Montilla et al 2008). This residue has an energy potential for transformation into synthesis gas by the gasification process.

In Colombia, the average annual coffee pulp production is 2.25 tonnes/ha which represents about 162,900 tonnes of fresh coffee pulp per million bags of 60kg of coffee (Rodriguez and Sambrano 2010). This by-product can become a decentralized source for generating sustainable energy for the thermal requirements of coffee drying.

Biomass gasification is a thermo-chemical process that transforms the chemical energy of a solid residue into a gas with variable energy potential depending on the type of reactor and the gasifying agent. The use of gaseous fuels is considerably more practical than solid fuels. A gas is easily distributed to different locations where required and the combustion is controllable. Furthermore, the ignition time of a solid fuel is higher. Synthesis gas has the potential to be used in internal combustion engines for direct mechanical power or electricity generation. Considering the organic origin of the fuel, it is projected as a sustainable energy alternative with a minimum environmental impact (Giraldo 2012).

The aims of the study described in this paper were: (i) to develop the conceptual design, and the construction and commissioning of a downstream biomass gasifier which uses residual biomass from the coffee pulp as fuel; and (ii) to generate a synthesis gas for supplying the heat source required for the drying of fresh coffee beans.

Materials and methods

Location

The construction and preliminary tests of operation were carried out at the University Foundation for Tropical Agriculture - UTA, Municipality of GuapotÃ¡, Santander, Colombia. The drying tests were carried out in the farm La Emilita, Municipality of Calarca, QuindÃo, Colombia; recognized at the departmental level for its high-quality coffee

Biomass

There are a variety of sources of residual biomasses that may be used in the gasification process; however, aspects such as availability, acquisition costs and particle size play a very important role when selecting which one is going to be used in the gasifier.

For a preliminary evaluation, three types of biomass were selected: rice husk - RH (used as bedding in animal husbandry and as substrate in hydroponic crops); coffee husk or "cisco" CH (from the threshing process of the dry parchment coffee available in the collection centres) and coffee pulp - CP (generated during the wet process of separating the bean from the cherry). In the preliminary tests of gasification of these sources of biomass, emphasis was put on the need to avoid pre-treatment processes such as densification or crushing.

Conditioning of biomass

The operation of gasification equipment requires material with uniform size and with low humidity (Garcia 2005). In this study, the three pre-selected sources of biomass had a particle size between 2 and 3 mm, ideal for the type of gasifier selected. Therefore, there was no need to adjust the particle size. However, before submitting these residues to the gasification system an initial solar drying process was necessary to adjust the humidity to between 10 and 11%.

For RH and CH, little drying time was required, since these materials are commercialized with low humidity percentage. In the case of CP, it had a high initial moisture content of about 80%. Preliminary tests showed that it took 4 to 5 days to obtain the desired humidity percentage for the correct operation of the gasifier, by solar drying under a plastic canopy. The loss of moisture as a function of drying days can be seen in Figure 1.

Figure 1. Drying curve of coffee pulp

The major loss of moisture in coffee pulp, from 80 to 18%, occurs during the first four days. However, the rate of drying will necessarily depend on the drying process (open paved surfaces or under plastic canopies) and the meteorological conditions at the site (solar intensity, ambient temperature and relative humidit

Gasifier

Fixed-bed gasification equipment is generally classified as Updraft and Downdraft mode, in accordance with the direction of the gas flow and the solid to be gasified. The updraft gasifier is simpler in construction and has the possibility to operate with a greater variety of biomass. Its main disadvantage lies in the greater production of tars that can cause obstructions and increases the needs of equipment maintenance (Garcia 2005). The Downdraft gasifier has 4 characteristic zones: drying, pyrolysis, oxidation and reduction, denominated as a function of the physical or physicochemical changes that the biomass undergoes in these zones according to the temperature. This configuration allows part of the tars formed in the reactor to be forced through the high temperature zones before leaving the equipment and thereby undergoing a thermal decomposition which favours the calorific value of the gas and reduces its temperature (Garcia 2005).

The composition of the gas depends on the biomass used, the oxidizing agent and the type of gasifier. It consists mainly of hydrogen H_2, carbon monoxide CO, carbon dioxide CO_2, traces of methane CH_4 and Nitrogen N_2; (Garcia 2005). Hydrogen and carbon monoxide are the main fuel gases of the mixture (Gaetana 2007).

The proportion of residual solid material (known as biochar) is a function of the biomass and the gasifier operating conditions. Recent studies in small biomass gasifiers indicate that the rate of air flow has an inverse effect on the production of biochar as the reactor temperature increases and the portions of H and CO in the synthesis gas increases (Lanh et al 2016).

Biochar is considered a valuable by-product of the process and plays an important role when applied directly to soil where it acts as a carbon sink as well as increasing plant growth (Preston 2015) through its support for biofilms (Leng et al 2014).

Figure 2 illustrates the different parts present in the types of gasifiers mentioned above, the feed flow direction and the synthesis gas.

Figure 2. Fixed bed gasifier Updraft (left) and Downdraft (right) (from Garcia 2005).

The design and construction of the gasifier used in the present study was achieved by decreasing the scale of a commercial gasifier (Ankur Scientific Energy Technology Pvt Ltd, Model WBG-10) operated in the farm of the UTA foundation since 2005.

The gasifier was designed to work with tree prunings waste and wood, which generally implies an additional energy expenditure for the conditioning of the biomass in small pieces that guarantee a constant flow from the hopper to the reactor (Preston and Rodriguez 2009). Previous experiments with this gasifier proved that it was possible to use low density biomass such as cane bagasse or forage tree stems, showing good results in synthesis gas production and stable operation. However, the low bulk density of the material made hampered the flow of biomass into the reactor, requiring periodic agitation of the contents of the hopper.(Rodriguez and Preston 2010).

The prototype downdraft gasifier developed in this study was designed to be loaded through a hatch with hermetic seal. The material is stored in a vertical cylindrical container with a capacity of 75 liters. Inside this contained a worm-type agitator is fitted, with the aim of facilitating a continuous flow of the contents to the reactor.

The oxidizing agent (air) was supplied by a radial fan directly into the reaction zone through a carbon steel tube. The residual solid matter (biochar) and the synthesis gas leave the reaction zone through perforations in the reactor wall aided by the action of a motorized blade powered by an electric motor situated below the gasifier. The reactor was located inside a metal jacket with a space between them to receive the synthesis gas and the biochar. The synthesis gas exits the metal jacket through a 7mm id steel pipe; the biochar is evacuated to the outside by a screw.

The electric motors driving the biomass agitator, the screw for removal of the biochar and the fan feeding air to the reaction zone, operate at 24 Volts DC, thus representing minimal risk to the operator of electric shock.

Preliminary tests of the gasifier operation

During operation of the gasifier the aim was to maintain a continuous stream of fuel gas so as to facilitate the transfer of energy through the heat exchanger to the air stream that enters the silo-dryer. Tests were conducted to rate the relative values of each source of biomass previously listed (RH, CH and CP), with the aim of continuing to the next stage of development of the study. The tests were performed with the prototype gasifier and focused on identifying the advantages and disadvantages of the operation with each source of biomass, in terms of stability in operation, as measured by the production and constant combustion of the synthesis gas, production of tar and biochar.

The gasifier operating conditions - oxidant agent flow and residence time in the reactor - were fixed; the factor that was evaluated was the type of biomass.

Silo-drier

The equipment used for the tests of drying the coffee was a rectangular enclosure, constructed of metal sheets with dimensions of: 1.33m height, 1.03m width and 0.63m depth; the internal space was divided transversally by 3 metal mesh trays.

The fan for the drier was directly coupled to a Â½HP motor at 1,800 rpm, which provided the required flow rate and pressure so that the upwardly rising hot air passed through layers of coffee with a depth of between 0.13 and 0.15m. The humid air exited the silo at the top.

Normally, the heat required for drying is supplied by the combustion of LPG in a venturi-type burner located in the fan suction pipe (Photo 1). The air temperature is maintained at approximately 50Â°C, by adjusting a valve before the burner. The system has an “NC” solenoid valve which is electrically linked to the fan motor and cuts off the gas when the engine is stopped by shutdown or failure.

Gas consumption was 0.5kg per 7kg of dry coffee, meaning that a 20kg gas cylinder was required to dry 280 kg of coffee (Estrada 2017).

Photo 1. Commercial silo-drier fuelled with LPG
(Source; Estrada 2017)

Silo adaptation

For the adaptation of the gasifier to the silo-drier, an exchanger was constructed which facilitates the transfer of the heat generated in the combustion of the synthesis gas to the air stream generated by the silo fan, thus avoiding contamination of the coffee beans from odours and particulate matter from the gasifier. A flexible aluminium duct of 10cm diameter connects the flange that secures the propane burner, with the heat exchanger. The propane burner was removed for the silo operation. During the test a comparison was made between the conventional drying system using propane gas and the proposed biomass gasification system (Photo 2).

Photo 2. Adaptation of the silo-drier to accept the hot air stream from the gasifier heat exchanger.

Methodology

Coffee drying

To evaluate the viability of the silo conversion, two tests were performed to determine the drying time and fuel consumption: the first using LPG and the second using synthesis gas. These tests were performed with the synthesis gas derived from the biomass selected from the preliminary evaluation. The silo was loaded with an average of 32kg of coffee which had been partially dried for 5h under a traditional plastic canopy.

Analyses

The moisture in the coffee was determined with a portable equipment (MT-PRO, brand AgraTronix) which had a measurement range of 5 to 40% moisture. The equipment was designed to operate in a temperature range of 0 to 40Â°C with a stated accuracy of Â± 0.5%. Measurement of the biomass was carried out with a digital scale with a resolution of 10g and a maximum capacity of 60 kg.

Results and discussion

Preliminary test of the gasifier

The gasifier operated according to expectations (see the Video).

It was evident during the tests that the gasifier needed a stabilization time to obtain a stream of stable and combustible synthesis gas. The dried coffee pulp produced a synthesis gas of more uniform quality as compared with the rice husks and the coffee husks (Table 1). The time to stabilise the gas flow and the rate of consumption of biomass also favoured the use of coffee pulp compared with the other feedstocks.

By contrast, the relative production rate of biochar was higher for rice husk compared with coffee pulp and cisco" which did not differ. The quality of the biochar, as indicated by its capacity to absorb water was also highest for the rice husk biochar. The coffee pulp was associated with a minimum degree of obstruction of the pipes by tar, in contrast to the coffee husks that produced more tar. Biochar contamination of the synthesis gas stream was also apparent when the fuel was rice husks or coffee husks due to their lower density compared to the coffee pulp.

Table 1. Effect of source of biomass on operational characteristics of the gasifier, and on the quantity and

Biomass	Load (kg)	Fuel consumption (kg/h)	Stabilization time (min)	Operation time (min)	Biochar production

CP	9	2.5^{b}	27^{b}	200	18^{b}
RH	21	4.8^{a}	45^{a}	252	30^{a}
HC	20	2.7^{b}	45^{a}	420	19^{b}
SEM		,0.011	1.77		0.37
p		<0.001	<0.001		<0.001

[abc] Means without common superscript differ at p<0.05 # + Low, ++ Medium, +++High

It is concluded that the best biomass to use in this process is coffee pulp (CP). In addition, the selection of this type of biomass is cost-effective since it is available in all coffee farms, and thus does not imply an additional expense for the purchase of this material. Also, it does not require any additional pre-treatment such as densification or crushing; it only requires a moisture removal step.

Drying effectiveness

The moisture loss of the coffee beans during the drying process is determined by the initial moisture in the bean, the temperature of the hot air stream supplied to the silo (should not exceed 50Â°C), and the silo geometry which determines the height of the layers of coffee. The temperatures achieved in the dryer were similar for operation with synthesis gas as with LPG (Figures 3 and 4)

Figure 3. Temperature of the different areas of the drying silo using LPG

Figure 4. Te

Figure 5. Loss of moisture from coffee beans in operation with synthesis gas

The moisture loss from the coffee bean using Synthesis gas (Figure 5) shows the same tendency as with LPG (Figure 6); a rapid decrease of humidity in the first hour of operation and the subsequent slowdown of the process to reach the final moisture content.

Maintenance

The high temperatures of the gasification process impose a challenge for the durability (equipment life). Moreover, the generation and condensation of tars inside the gasifier, as well as in the conduction pipes of the synthesis gas, require inspections and periodic cleaning to avoid equipment clogging. Coffee pulp presents a smaller production of tars compared to other biomass tested during the gasifier adjustment stage.

Discussion

The drying of coffee beans using coffee pulp in a gasifier was successful. The gasifier can operate with different sources of biomass; however, it is necessary to optimize the gasifier geometries such as the hopper and the reactor, in addition to the oxidation air flow rates and the agitator configuration. Densification of the biomass can solve the problems of loading the reactor; however, it is desirable to minimize its preparation to avoid associated costs and maintain simplicity.

The results indicate that an additional source of biomass is necessary since the coffee production does not provide sufficient material. Other sources of biomass will be required.

The drying silo was not designed for the use of synthesis gas. Improvement and optimization of the design of the heat exchanger will lead to better use of the high temperature of the exhaust gases. It is advisable to pre-dry the coffee to reduce the time of operation of the silo.

Conclusions

- Coffee pulp is an appropriate source of biomass to use in gasifiers because of its particle homogeneity and low production of tars.

- The construction of the prototype Gasifier UTA 2.0 was carried out through manufacturing processes such as electric arc welding and basic, using materials available locally. This facilitates the replicability of the equipment so that it becomes a viable and economical alternative, compared with imported industrial equipment. The fact that the gasifier can be built locally has a direct impact on the generation of employment with technologies that use renewable sources of energy such as solar or wind, which at the moment are mainly of foreign origin.

- It is possible to adapt drying silos that use LPG to the gasification technology, in a flexible way which guarantees the continuity of drying with any of the available heat sources. It is possible to build a system of gasifier – coffee bean dryer, operable by a single person.

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