Two-stage pyrolytic conversion of coffee husk and parchment into synthesis gas

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Abstract. The paper considers the technology of two-stage pyrolytic conversion of biomass into gaseous fuel. Coffee husk and parchment were used in this study. The experimental data on composition and quantity of the gaseous products formed in the process of thermal treatment of husk and parchment are presented. The results indicated that the method allows obtaining more than 1.34 m$^3$ of synthesis gas, which consists 96-97% of hydrogen and carbon monoxide, with a heating value of about 11.7 MJ/m$^3$. At the same time, 26-29% of the solid residue (biochar) remains with a heating value of 27-31 MJ/kg. The resulting synthesis gas can be used for generating electricity and for producing liquid chemicals.

1. Introduction
Taking into account the limited reserves of fossil fuels, much attention in scientific research is paid to the development of renewable energy. The use of biomass as a fuel energy resource can reduce dependence on fossil fuels, and also helps to protect the environment. Coffee is one of the main agricultural commodities in the world and the second exported commodity after petroleum [1]. Its world production in 2017 was of approximately 9.5 thousand tons [2]. Coffee trees grow in equatorial and tropical latitudes, because they require a warm climate with stable temperatures and precipitation. The leaders in the production of coffee beans are Brazil, Vietnam, Indonesia, Colombia, India and others.

The character of waste generated depends on the type of coffee beans processing after harvesting. There are two main methods: dry and wet processing [3]. The fruit of the coffee tree have a complex layered structure: the outer skin or peel (exocarp), fleshy pulp and mucilage (mesocarp), parchment (endocarp) and the couple of coffee beans covered with thin silver skin [4]. In the dry processing, coffee berries are exposed to the sun or air dryers for several weeks, and then mechanically cleaned, removing the coffee husk, which is a mixture of peel, pulp, mucilage and parchment. The weight of the purified coffee bean is approximately 50% by weight of the dried coffee berry. Thus, with dry processing approximately 1 kg of husk is generating per every 1 kg of coffee bean [3]. Wet processing of coffee beans does not require long drying of berries, but includes several steps and is considered more complex from a technological point of view. First the outer skin and most of the pulp are mechanically removed by pressing of berries. In the next step, the remaining pulp and mucilage are removed by fermentation and washing. After that, the clean beans are dried to 12% moisture content and then de-hulled to remove the parchment (6.1% w/w from the whole fruit) [3]. Wet processing allows recovery of the coffee parchment separately from other fractions.
Coffee wastes can be converted into useful form of energy by applying two-stage thermo-chemical conversion technology of biomass, which is being developed at Joint Institute for High Temperatures of the Russian Academy of Sciences [5]. In the first stage, the raw material is heated in an oxygen-free environment to the final temperature of approximately 1000 °C (pyrolysis zone). The second stage lies in passing the vapour-gas mixture produced in the first stage through a carbon matrix at the temperature of 1000±5 °C (gasification zone). As a result of the interaction of volatile with carbon in the high-temperature zone, synthesis gas is formed, consisting mainly of carbon monoxide and hydrogen with an admixture of carbon dioxide, methane and nitrogen. The advantage of this technology lies in the high degree of conversion of the processed raw materials and the absence of a liquid fraction in the resulting gas.

The aim of this work is to study the possibility of recycling coffee waste using two-stage pyrolysis technology and to compare the characteristics of synthesis gas and biochar.

2. Materials and methods

2.1. Raw materials
Coffee husk (a mixture of peel, pulp and parchment) after dry processing and coffee parchment after wet processing of coffee beans were used in this study. Coffee husk (CH) and coffee parchment (CP) were provided by Kyagalanyi Coffee Ltd (Kampala, Uganda). Samples were dried at 105 °C to decrease moisture down to 1-1.5% by weight.

2.2. Experimental set-up and the process
Experimental set-up (figure 1) includes a reactor in the form of a steel pipe with a diameter of 37 mm and a length of 850 mm. The bowls are installed in the pyrolysis and gasification zones, tightly adjacent to the pipe walls and having perforation in the bottom for gas permeability. Initial raw materials were placed in the lower bowl (pyrolysis zone), biochar, previously heated in an inert medium at 1050 °C, was placed in the upper (gasification zone). The reactor is placed in a two-section electric furnace equipped with two autonomous controllers.

![Figure 1](image.png)

**Figure 1.** Scheme of the experimental setup: (1) two-section furnace, (2) pyrolysis zone of the reactor, (3) gasification zone of the reactor, (4) glass heat exchanger, (5) drum-type gas meter, (6) gas holder, and (7) gas analyzer.
Before the experiment, the setup was purged with argon to provide an inert atmosphere. At first, the gasification zone was heated to a temperature of 1000 ± 5 °C, which was held further at the constant level. The setup was purged again with argon. Then, the temperature in the pyrolysis zone was increased to 1000 °C at a rate of 7 °C/min. The gaseous and vaporous products formed during the pyrolysis process passed through biochar at the temperature of 1000 °C. As a result, the pyrolysis products were decomposed, forming mainly hydrogen and carbon monoxide. The resulting gas mixture was passed through a glass heat exchanger. The volume of non-condensable gases was measured by drum-type gas meter. The gas mixture was collected in a gas holder. The composition of the gas mixture was determined using gas analyzer.

2.3. The Analysis methods of raw materials and products

The elemental composition of the raw materials and the obtained biochar was determined using a Vario Macro Cube elemental analyzer (Elementar Analysensysteme GmbH, Germany). Ash content was determined according to ACTM E1755-01. The elemental oxygen content was determined by the difference. The higher heating value (HHV) of raw materials and biochar was calculated based on the elemental compositions. The composition of the gas mixture was determined using a Vario Plus Industrial gas analyzer (MRU GmbH, Germany). The HHV of the gases was estimated from the volume fractions and HHV of each gas component.

3. Results and discussion

Table 1 depicts the characteristics of raw materials and biochar obtained in terms of the dry state: element composition, ash content, estimated HHV and yield (for biochar only). As indicated in table 1, coffee husk has a significant amount of ash compared to parchment (7.74 and 1.61%, respectively). The elemental carbon content in the husk is slightly less than that in the parchment (45.14 and 49.96%, respectively). Obtained biochar has higher values of carbon, and lower percentages of hydrogen and oxygen when compared to raw material. This implies that the biochar became increasingly carbonaceous at high temperatures, releasing H and O. At the same time, biochar obtained from parchment has a much larger amount of elemental carbon compared to husk biochar (93.35 and 77.76%). As a result, the heating value of biochar increased by 49 and 57% compared with raw materials (from 18.19 to 27.19 MJ/kg for husk and from 20.16 to 31.77 MJ/kg for parchment). The yield of biochar from the husks and parchment is 28.92 and 26.20%, respectively. This means that 260-290 kg of biochar will be formed during the processing of 1 ton of husk or parchment by this method. The obtained biochar can be used for the gasification zone.

Table 1. The characteristics of raw materials and biochar.a

| Material | Element composition (wt%) | Ash (wt%) | HHV (MJ/kg) | Yield (%) |
|----------|---------------------------|-----------|-------------|-----------|
| CH       | 45.14 5.73 1.51 0.20 39.68 | 7.74      | 18.19       | -         |
| CH 1000c | 77.76 0.63 0.90 0.32 0.00  | 20.39     | 27.19       | 28.92     |
| CP       | 49.96 6.19 0.35 0.03 41.85 | 1.61      | 20.16       | -         |
| CP 1000c | 93.35 0.30 0.57 0.04 2.40 | 3.34      | 31.77       | 26.20     |

a On a dry matter basis.
b By the difference.
c Biochar obtained at 1000 °C.

Table 2 shows the characteristics of the obtained gas mixture, such as volume fractions, gas yield per 1 kg of raw material, estimated HHV and energy yield, which is calculated as the ratio of the HHV of synthesis gas obtained from 1 kg of raw material to the HHV of the raw material. The gaseous
mixture obtained by this method is composed of hydrogen and carbon monoxide in the amount of 96-97%. The yield of synthesis gas obtained by thermal conversion of two materials is approximately the same (1.35 for husk and 1.34 m³/kg for parchment). The HHV of the resulting synthesis gas is also close in value (11.71 and 11.76 MJ/m³, respectively). The energy yield is slightly different due to the difference in the HHV of the raw materials (86.9 and 78.2%, respectively).

**Table 2.** The characteristics of the gas mixture.

| Material | Fractions (vol%) | Gas yield (m³/kg) | HHV (MJ/m³) | Energy yield (%) |
|----------|------------------|-------------------|-------------|-----------------|
| CH       | 1.08 47.39 49.95 0.52 1.06 | 1.35 11.71 | 86.9 |
| CP       | 1.39 48.26 48.40 0.88 1.07 | 1.34 11.76 | 78.2 |

Figure 2 illustrates the gas yield as a function of the temperature in the pyrolysis zone. Figure 2 also shows the rate of gas generation as the first derivative of the function of the gas yield. It is observed that the thermal degradation of the coffee husk mainly occurs at temperatures between 140 and 600 °C and of coffee parchment occurs at temperatures between 200 and 600 °C. At the same time, the peak of gas generation occurs at 280 °C for the husk and 310 °C for parchment.

In [6], where the results of studies of the slow pyrolysis of coffee husk briquettes are presented, it is indicated that significant mass loss occurs in the temperature range of 130-430 °C. And the maximum rate of decomposition is observed in the temperature range of 277 and 292 °C. This is in good agreement with the data obtained for the coffee husks. The mass loss of raw material during pyrolysis is associated with the release of volatiles, therefore, directly affects the rate of gas yield in the second stage of the process.

**Figure 2.** Dependence of gas yield on temperature in the pyrolysis zone.

4. **Conclusions**

The two-stage thermal conversion of coffee husks and parchment allows getting more than 1.34 m³ of synthesis gas from 1 kg of dry biomass. The resulting gas with a heating value of about 11.7 MJ/m³.
consists of 96-97% carbon monoxide and hydrogen. It must be borne in mind that material samples were dried before the experiment, since increased humidity can reduce the energy yield. The resulting synthesis gas can be used both for generating electricity and for producing liquid chemicals mainly for fuel purposes. At the same time, the geographic spread of the proposed method of coffee wastes disposal is limited by the tropical and subtropical coffee-growing regions.

5. References
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