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DEVELOPMENT OF LAB-SCALE GASIFICATION SYSTEMS FOR DIFFERENT POSSIBLE APPLICATIONS

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ABSTRACT

The goal of gasification is the conversion of solid fuels or carbonaceous wastes to gas that can be further used energetically or for chemically utilisation. Due to cost-effectiveness and gaining experience, the industrial application of new systems and raw materials or mixtures must be preceded by laboratory-scale experiments. The manuscript presents the laboratory scale gasification systems that were designed and used in the Institute of Energy, Ceramics and Polymer Technology at the University of Miskolc, as well as the difficulties experienced during the implementation (e.g. water introduction, sealing, etc.). In addition to these, the results of one-, two- and three-stage experiments are presented as examples, where different materials such as a mixture of wood and canteen waste, brown coal and refuse derived fuel (RDF) were used for testing the system.

Keywords: gasification, lab-scale, experimental system

1. INTRODUCTION

The energy demand is increasing worldwide every year [1], with natural gas substitution predicted to come to the fore in order to achieve carbon neutrality [2]. In addition, countries, including our country, must strive to reduce their energy dependence [3]. This can be facilitated by the increase of the utilization of renewable energy sources, the use of non-conventional raw materials in energy production, or the development of environmentally friendly fuel conversion technologies.

One such technology is gasification, which is a thermochemical process. This is usually carried out above 800 °C in an oxygen-deficient environment. During the process, the carbon-containing raw material undergoes partial oxidation, which can be achieved by controlled dosing of the gasification medium (e.g. air, oxygen, water, steam). The goal is the conversion of the solid raw material into a gaseous energy carrier, as much as possible. This energy carrier typically has a high content of hydrogen and carbon monoxide, so it is not only suitable for energetic applications, but can also be used as a raw material for the chemical industry. Gasification is considered one of the clean coal technologies, which will be an important trend in future coal use. In addition, it can be a solution for the utilization of many wastes, even in cases where waste can only be thermally disposed (e.g. infectious or other dangerous substances) [4]. In addition, the gasification of biomasses also has great importance in the production of raw materials of high value-added chemicals.

Before industrial-scale gasification of a raw material or mixture of raw materials, the testing of raw material is necessary, and it is worth conducting experiments on a laboratory scale in order to determine the optimal operating parameters (e.g. temperature, pressure, amount of gasifying medium, etc.). During testing, the behaviour of the raw materials, the properties of the products formed, etc. can be examined. Gasification technologies have been studied and used for several decades, and accordingly, there are many types of lab-scale versions in the literature from the simplest to the most complex, multi-stage systems.

An example of the use of a smaller system was demonstrated by Sieradzka et al. [5]. They investigated the CO_2 gasification of biomass wastes. The amount of sample was 8 g and the carbon dioxide flow rate was 80 mL/min. Prabowo et al. [6] published an article, in which a small-scale downdraft gasifier was used. The base material was rice straw (3.5 g), the gasifier worked at 950 °C with CO_2 and steam as gasifying agents.

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An example of a larger system was given by Moshi et al. [7]. They used a low temperature fixed bed gasifier, where the base material was municipal solid waste, the feed rate was 6 kg/h and the gasifying agent was air. Lab-scale fluidization systems using different amounts of material are also available in the literature. Hervy et al. [8] carried out continuous fluidized gasification of solid recovered fuel at a feed rate of 2.3-5.9 kg/h. The fluidising media and the gasifying agent were air. Katsaros et al. [9] used fluidised air gasification for poultry litter at 700 °C, where the feeding rate was 0.55 kg/h. Li et al. [10] applied a bubbling fluidized bed reactor with steam for the gasification of 2 g of polyethylene terephthalate (PET). Jeong et al. [11] used a lab-scale two-stage reactor (fluidised bed and tar-cracking reactor) for biomass gasification. The flow rate of biomass was 1.2 kg/h, the temperature was approximately 780-800 °C. Grandhi et al. [12] described the sizing and design of a lab-scale downdraft gasifier. Dong et al. [13] applied a rotary feeder conveyor for the transporting of biomass particles into our lab-scale reactor. The gasifying agents were steam and oxygen, the maximum temperature was about 900 °C, and the feed rate of base material (woody biomass) was 2 and 4.4 kg/h.

In addition to commercial use, more extreme research examples can also be found. For example, Meier et al. [14] investigated the use of plasma arc gasification to convert high fidelity waste simulant on long duration space missions into useful commodities. The temperature of the gasification was above 900 °C, and the mass off the sample was 600 g in each experiment.

Based on the literature and our experience, it can be concluded that a few grams of sample may be sufficient to carry out some tests. If it is necessary to monitor the change in the gas composition, the intensity of gas formation, the material and element balances, or the produced liquid and the residual coke/ash should be examined, at least 20-30 g of raw material is required. According to the literature data, the simplest and most cost-effective method to investigate the basic processes is with a fixed-bed reactor with intermittent operation. Using the laboratory experiences of the past years, the goal was to prepare a manuscript that can help researchers performing laboratory gasification, to design systems and to avoid the pitfalls of designing small-scale systems.

2. THE DEVELOPMENT AND DESCRIPTION OF THE EXPERIMENTAL SYSTEMS

2.1. One-stage gasification system

The basic set-up of the one-stage gasification system is illustrated in Figure 1.

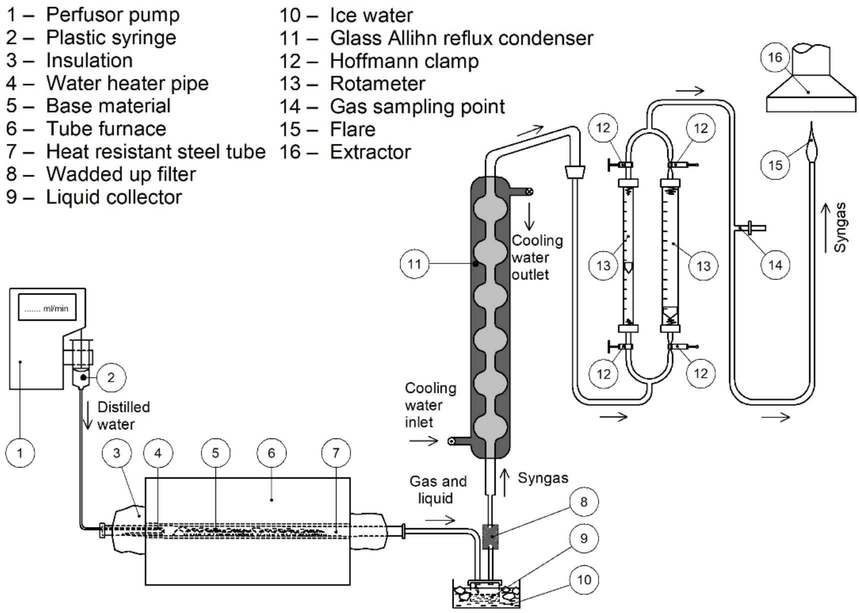

Figure 1. Schematic of the one-stage laboratory gasification system

To properly control the gasification process, an electric heating system is necessary. The easiest method is the implementation of a tube furnace with external heating, with an acid- or heatproof steel reactor. The former reactor can be used for experiments at 800-900 °C, while the latter is applicable for higher temperatures as well. Contrary to vertical placement, the advantage of a horizontal reactor is the simplicity to flush with inert gas so that it can penetrate the interparticle space between the feed. Approximately 40-60 g feed produces a sufficient amount of product for most analyses. A tubular reactor with ¾” diameter for furnaces with a 20-25 cm long heated zone is applicable for such an amount of raw material.

Preparing both ends of the reactor with screw threads made the assembly easy. Heat-resistant silicone was used to seal the screw thread ends. Some of these silicones can be applied at 340 °C, such as cylinder head gasket silicone paste, so the connective parts of the reactor should be below such temperatures. One of the most critical issues can be the introduction of the gasification medium to the system, which was carried out through one side of the tube reactor through a hex pipe cap, sealed with silicone. On a laboratory scale, the production and introduction of a sufficient amount of water vapour is hard to achieve. Thus, the gasification medium was added as water and then evaporated inside the reactor.

The produced gases exit from the reactor at the opposite side of the water feeding unit. This end of the reactor can simply be connected to other parts of the system with a union fitting. If rubber sealing is used, the temperature of the fitting should be below 80 °C. In the case of silicon sealant, the fitting can withstand higher temperature, thus, can be placed closer to the heated zone.

The next step is the rapid cooling of the produced gases to condense the non-reacted vapour and the hydrocarbons with high carbon number. Such liquids are discharged into a liquid collector inside of a water cooler. If the changes in the gas production intensity need to be examined, the removal of all condensable hydrocarbons is essential. For this purpose, a filter filled with cotton and a reflux condenser can be used. The hydrocarbons condensed in these units cannot interfere with the operation of the rotameters.

There are many advantages if the various parts of the system are connected with silicone tubes. Silicon tubes are capable of elastic deformation, can provide airtight connection to fittings with significantly larger ends, and can be used above 100 °C. An additional benefit of silicon tubes can be observed during the gas sampling process. When instruments from the medical industry, such as syringes or intravenous equipment is used for sampling, the tube can be punctured with a butterfly needle for an airtight sampling and simple fastening. The developed gas sampling method is described in the publication of Nagy et al. [10]. The produced gas can be continuously burned with a flare or collected into a gas sampling bag if it is later used as a base material for other experiments.

2.2. Developing the water feeding unit

The possible methods of water addition to the reactor that were tested can be seen in Figure 2.

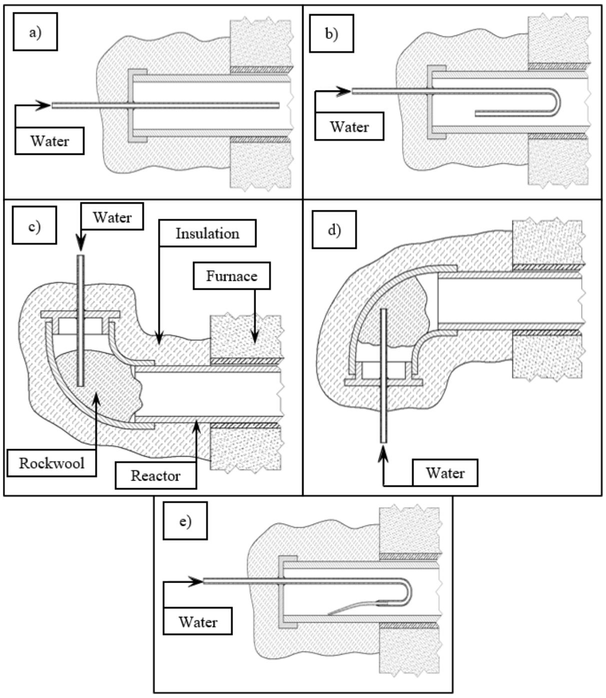

Figure 2. The tested methods for the introduction of water as a gasification medium

The water addition can be precisely regulated with a perfusor pump, the exact type for the experiments was a Medex Medfusion 2010 which can sustain 0.1-350 mL/h flow rate. According to the first build, if water enters the reactor via a thin tube (Figure 2/a), the water droplets instantly evaporate after getting in contact with the reactor wall, and the produced vapour flows through the system in a few seconds. Thus, there is no time for the solid-gaseous phase reactions and the water will condense in the liquid collector without utilisation.

In Figure 2/b, the addition of a pre-heating section can be seen. In this case, water can reach the heated zone and evaporate in the reversed part of the tube. This method provided a more uniform gas yield, however, impulse-like increases were recorded in the gas yield due to the occasional water droplets in the system.

The next tested method was the addition of a small piece of rockwool that could properly heat up, providing sufficient and continuous evaporation of the water in the tube, as seen in Figure 2/c and 2/d. The issue in this case was the determination of the optimal amount (length and compactness) of rockwool and the consequent water flow rate. If water is fed from the bottom (Figure 2/d), the excess water will be collected in the hex pipe cap and only a small portion will evaporate. But if water is fed from the top vertically (Figure 2/c), the inadequate water flow rate can cause the water to flow through the rockwool and gather at the end of the reactor.

One of the best solutions proved to be the method seen in Figure 2/e, when the water/vapour was fed to the wall of the reactor at the end of the pre-heating zone, via a tube with 0.5 mm inner diameter. This developed water feeding system produced the most uniform gas yield and was subsequently used in the final build.

2.3. Multi-step gasification systems

Additionally to the basic gasification experiments, multi-step systems can be modelled with the use of several heated zones (more furnaces). Some of the tested setups can be seen in Figure 3.

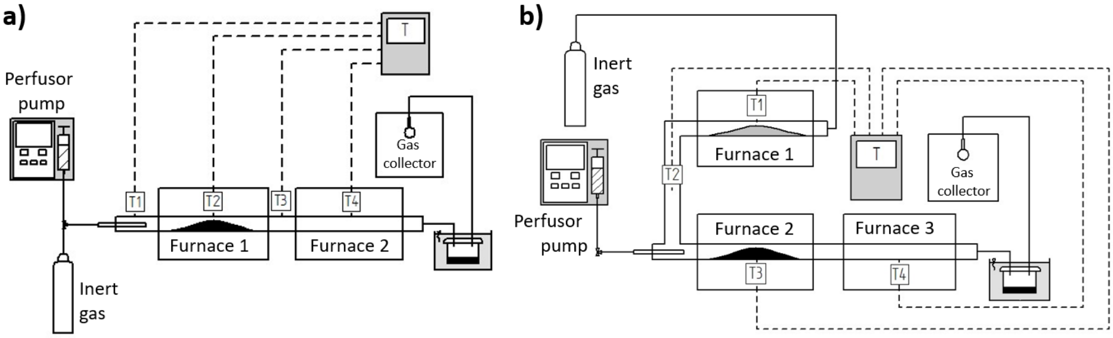

Figure 3. Sketches of a two-stage (a) and a three-stage (b) lab-scale gasification system

During gasification, hydrocarbons with varying carbon numbers are produced, though, their quantity is generally small. As the presence of these components is not favourable for chemical industrial use, their separation or decomposition is necessary. The system can be compatible with such experiments via the increase in the reactor length and the number of heated zones (Figure 3/a). Furthermore, the subsequent heating zones can be loaded with catalysts (e.g. for tar-cracking [6]) or material applicable for sulphur adsorption as well.

Using three heated zones (Figure 3/b), pyrolysis, gasification, and the catalytic or thermal decomposition of the hydrocarbons can be achieved in the same system. The developed multi-step (containing multiple furnaces) system can be highly space efficient, as it can be operated horizontally and vertically as well, e.g. inside a laboratory fume extraction chamber.

The application of multiple furnaces makes it possible to add the gasification medium between zones. Furthermore, inerting the system and removing the produced gases can be achieved by flushing the system with inert gases, such as N_2 or Ar, at several different parts of the system. A significant step when preparing multi-furnace systems is the appropriate heat insulation between the furnaces to prevent condensation. Moreover, heat resistant silicone is not applicable for sealing the screw threads between the furnaces. At these parts, fire place sealants with high heat resistance should be used.

The experimental systems prepared based on the above-mentioned information can be seen in Figure 4.

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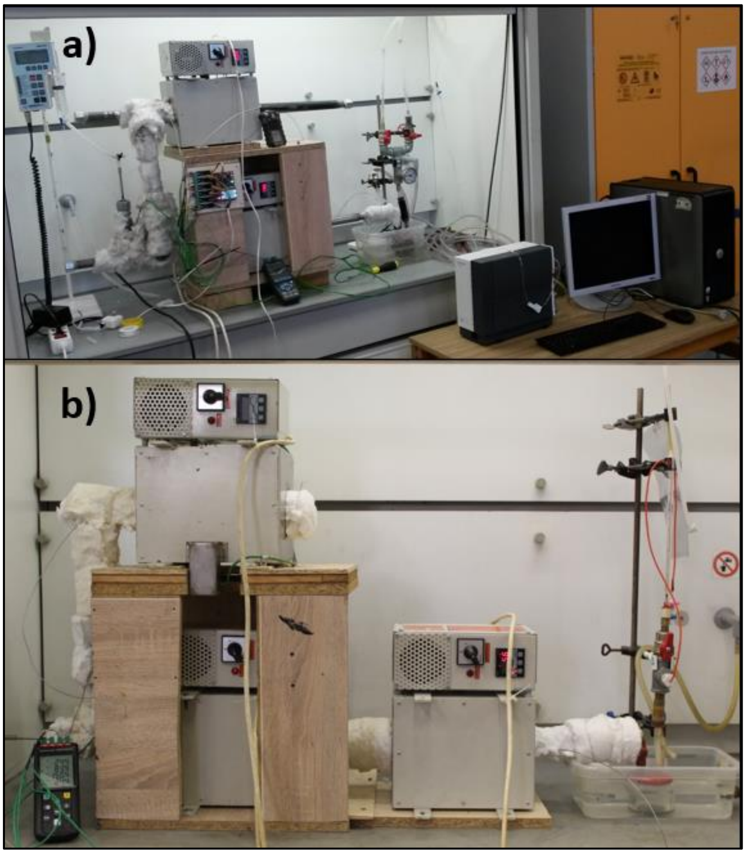

Figure 4. Photographs of a two-stage (a) and a three-stage (b) experimental gasification system

3. EXAMPLES OF APPLICATIONS

3.1. One-stage gasification experiment

During a set of experiments, we investigated the possibility of gasifying oak and canteen waste mixture. Canteen waste is produced in large quantities in developed countries, their organic matter and moisture content are high, but when mixed with other materials, they provide a suitable basis for gasification. Figure 5 shows the gas yields during some experiments where the raw material was oak and canteen waste mixed in a 2:1 mass ratio, the amount of sample was 30 g, the temperature varied between 700 and 900 °C, and the water dosage was changed between 7 and 22 mL/h.

Examining the effect of the temperature, it was found that the gasification reactions are only partially completed at 700 °C, at least 800 °C is required for higher gas yield. The amount of gasifying medium also affects gas formation. By increasing the amount of water, the amount of produced gas increases. As a result, the amount of unreacted water also increases proportionally with the gas, so this must be optimized during each experiment.

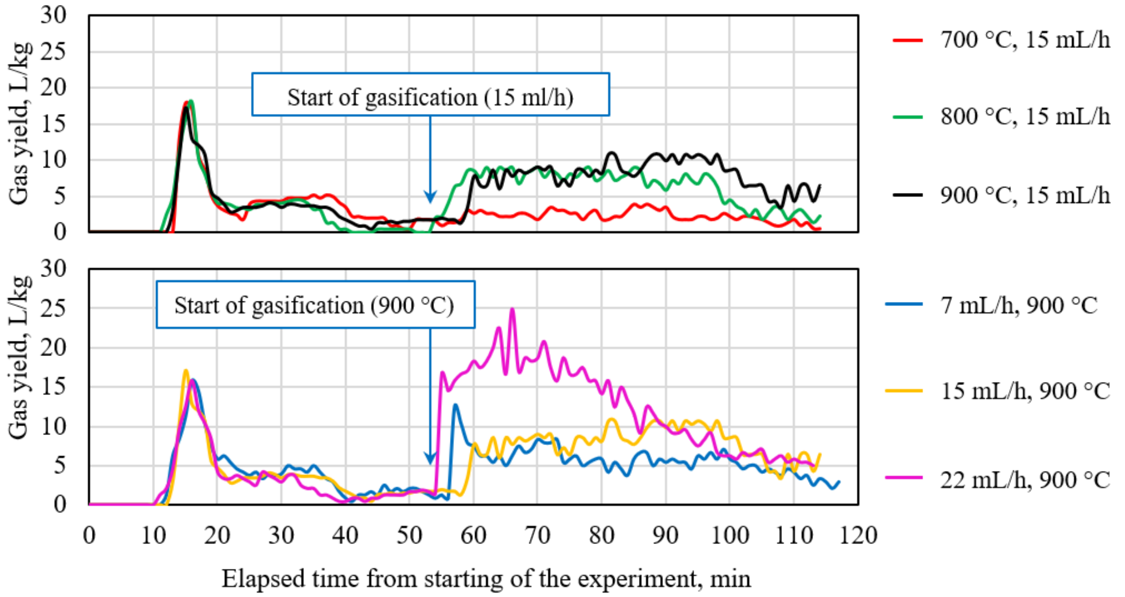

Figure 5. The changes of gas yield during the gasification of oak and canteen waste mixed in a 2:1 mass ratio

3.2. Two-stage gasification experiment

In another series of experiments, the pyrolysis and gasification of brown coal was investigated in a two-stage system. In Figure 6, a comparison of the average gas composition formed in a one- and two-stage system can be seen after pyrolysis. Using a two-stage system (longer heated zone), the large hydrocarbons were partially decomposed, which is shown by the increased gas yield. Based on these results, the two-stage system was used for further gasification experiments, using a reactor temperature of 900 °C and a water dosage of 10 mL/h. As a result of the experiments, it was concluded that by using the same amount of material and increasing the length of the heated zone by using two furnaces, the amount of formed tar could be reduced during gasification. Thus, the application of the two-stage system for gasification had positive effect on both the gas yield and the tar-cracking for brown coal samples.

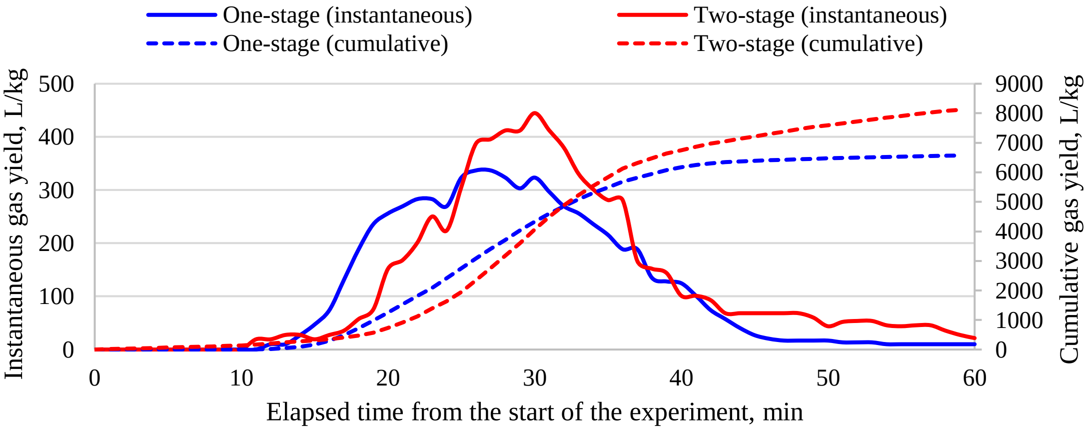

Figure 6. Instantaneous and cumulative gas yield during one- and two-stage pyrolysis of brown coal at 900 °C

3.3. Three-stage gasification experiment

Tar-cracking experiments were investigated in a three-stage system and compared with results from separately applying one-stage pyrolysis and one-stage gasification. The results shown in Table 1 were obtained during the pyrolysis and gasification of RDF. RDF is a combustible sub-fraction of municipal solid waste. During the experiment, pyrolysis took place in Furnace 1 (Figure 3/b) at 600 °C, where 20 g of RDF was added. Furnace 2 contained 10 g of RDF coke, where gasification took place at 900°C with 10 mL/h of water flow rate. Furnace 2 also served as a tar-cracking reactor, which was supplemented by Furnace 3 operated at 900°C. Such use of the three furnaces is applicable to model a system with continuous operation. Based on the results, it can be concluded that the amount of tar formed can be significantly reduced under such conditions. This was shown on the one hand by the increase in gas yield. The total amount of gas produced during pyrolysis and gasification applied in a separate system was 20% less than the gas yield measured when the three stages were connected. In addition to these, the amount of non-condensable hydrocarbons increased by nearly four times as a result of the decomposition of the tar.

Table 1. Results of experiments aimed at tar-cracking formed during pyrolysis

Gas parameters	Separately applied pyrolysis and gasification	Three-stage pyrolysis and gasification
Yield, L	24.6	29.5
H_2, (vol%)	57.8	54.9
CO, (vol%)	22.5	17.7
CO_2, (vol%)	14.4	16.4
C_xH_y, (vol%)	1.9	7.7

4. SUMMARY

Carbon-based solid energy carriers and waste can be converted into synthesis gas at high temperatures during gasification. Due to its high content of hydrogen and carbon monoxide, it can also be used as a base material for chemicals with a higher added value. For years, there have been laboratory-scale gasification experiments with self-designed and constructed systems. The article presents the design of the basic one-stage gasification system, as well as its two- and three-stage versions. The details that are worth considering during the construction of the system (e.g. choice of sealing materials, water introduction, etc.), and some experimental results were also presented. The different systems can be applied for various materials and research purposes. Each system has its advantage, depending on the types of experiments that need to be carried out. Overall, the presented designs and results can provide useful information for researchers as a basis for the preparation and issues related to self-built gasification systems.

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