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Design and Implementation of a New High-Flow Biomass Gasifier Based on Physics-Driven Model

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Abstract

In contrast to combustion, gasification is assumed to be caused by a lack of oxygen. One can remove this paradigm by inverting the causality chain: the gasification process is not the result but the origin of less oxygen consumption (compared to combustion). A new construction principle for gasifiers derives from this, and a gasifier built accordingly can test whether removing the traditional paradigm makes sense. The first results from a new type of gasifier that operates with abundant primary air are shown in this paper. The gasifier has a very high power density (10 kW/l) and can process waste biomasses unsuited for traditional gasifiers.

Keywords

Renewables, Biomasses, Gasifiers

1. Introduction

Owing to the rapidly growing global population and increased industrialization worldwide, there has been a considerable escalation in the energy demand. This trend is further accentuated by the depletion of fossil fuel reserves and the escalating environmental issues stemming from their extensive exploitation. According to international energy agencies, energy production and use account for about two-thirds of worldwide greenhouse gas emissions, placing the energy sector at the heart of climate change programs. Consequently, a swift shift towards embracing clean, sustainable, and secure energy sources is taking place. In light of these advancements, it is imperative to develop low-emission technologies alongside the transition to renewable energy sources, which serve as vital substitutes for fossil fuels in energy generation. Biomass emerges as an environmentally friendly energy

source with global availability, offering lower environmental repercussions compared to traditional fuels [1] [2]. Its utilization in energy conversion deploys various biochemical and thermochemical techniques such as combustion, pyrolysis, gasification, and liquefaction [3]-[5]. Gasification is the conversion of biomass, or any solid fuel, into an energetic gas through partial oxidation at elevated temperatures (syngas), surpassing combustion and pyrolysis in producing a cleaner gas. The syngas constitutes a mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), small quantities of other light hydrocarbons (C_nH_m), carbon dioxide (CO_2), besides the nitrogen (N_2) present in the primary air. Gasification also can result in variable quantities of pyroligneous acids and tars [6] [7]. Tar formation is one of the biggest problems faced during biomass gasification. The tar condensates under reduced temperatures, polymerizing in equipment such as engines and turbines [8]. Until about 40 years ago, in many countries, the so-called "town gas" [9] was used instead of natural gas, nowadays common. Town gas was locally produced from the gasification of fossil fuels, usually coal, with a process that was not CO_2 neutral. From the beginning until the large-scale usage of natural gas, more than 50,000 manufactured gas plants [10] were active in the United States.

Gas manufacturing generated several by-products, contaminating the soil and groundwater in and around the manufacturing plant [11]. For this reason, many former town gas plants were a serious environmental concern, and cleanup and remediation costs were often high. These plants were frequently built in the proximity of waterways to facilitate the coal arrival and get rid of wastewater contaminated with tar, ammonia, and drip oils, as well as outright waste tars and tar-water emulsions [12].

During both world wars, especially during World War II, wood gas generators (Gasogene or Gazogène [13]) were used to power trucks, buses, and agricultural machines in Europe [14], due to the lack of petroleum [2]. If biomass is gasified instead of fossil fuels, the process is CO_2 neutral.

The technology is sustainable, and wooden gasifiers are still built and used. However, they are not widespread mainly for three reasons:

- state-of-the-art devices tend to be characterized by large dimensions [15] and are therefore expensive;
- biomass gasifiers usually need high-quality combustibles such as wood and, for example, cannot process straw. The ash of straw has a low melting point (around 700˚C) [16]: as a consequence, state-of-the-art gasifiers get eventually blocked and stop operation. Several studies of this problem exist [17], and it has also been suggested to increase the melting point using additives, such as sand;
- conventional gasifiers tend to produce tar [7]: devices or procedures to minimize the tar content increase the complexity and, therefore, the price of these devices [8].

All of the mentioned devices are, or were, based on a paradigm: gasification results from a lack of oxygen (discussed in more detail in the next chapter). This article intends to question that paradigm and explore whether a gasifier can be

built, which uses an abundance of primary air. If this is possible, it would also become possible to create one single (and long) homogeneous gasification zone, instead of a sequence of gasification zones, which are separated from each other, as is the case in commonly used modern multi-stage gasifiers. The increase in airflow induces an increase in biomass flow through this new gasifier, which here and in the following will be referred to as a "high-flow gasifier". This new device was developed by the academic spin-off company Isomorph srl [18]. Questions investigated in this paper are: 1) does this high-flow gasifier work under typical biomass-gasifier operation conditions (wood gasification at about 700˚C)? 2) Can this high-flow gasifier also work at untypical low temperatures and gasify straw? 3) Can this high-flow gasifier also work with waste biomass (biomass that is not used but is left to decompose), usually not processed in standard devices?

The purpose here is to give a "proof of concept" while a systematic study of all the different operation conditions will be the subject of future investigations. Traditionally it is assumed that gasification is obtained with a lack of oxygen: "If the oxygen supply is restricted, one can gasify the carbon into carbon monoxide" [19].

This paradigm presumably derives from the development of combustion engines where a well-defined quantity of oxygen finds a well-defined amount of fuel, and therefore the stoichiometric ratio is well-defined. However, from a physics point of view, this paradigm is not understandable in the case of a gasifier. If a certain quantity of air enters a reactor containing biomass [20], it is not clear a priori what fraction of the biomass will participate in the reaction. This paper therefore suggests not to consider gasification to occur as a consequence of a lack of oxygen, but rather to invert the causality chain: a gasification reaction will cause a smaller consumption of oxygen per unit mass of processed material, compared to a combustion reaction.

These two different points of view have different consequences for the construction of a gasifier: If gasification is caused by a lack of air, then it is natural to let primary air enter the reactor only at one point, creating a reaction zone at this point. If one wants to increase the power of the gasifier, or if one wants to reduce the tar content of the gas, one will create additional reaction zones, separated from the first one, to avoid an increase in airflow in the first reaction zone. The multi-stage designs of the modern gasifiers is a consequence of this consideration.

Without the assumption that an increase in airflow will change the gasification reaction to combustion, there is no need to create several different gasification zones. Rather, one can add air inlets near each other to create a single large reaction volume. This will be described in more detail in section.

2. Design and Functioning of the New Gasifier

The easiest way to increase the airflow in the gasifier would be to do it through the inlet. However, this could raise too much the temperature: the gasifier described here, built from stainless steel, should not exceed working temperatures of about 800˚C. Instead of producing a small but very hot gasification region, one

can try to have a larger gasification volume (one single stage), at a temperature that is high enough for gasification, but below 800˚C.

This is explained in Figure 1 which sketches a tube through which biomass moves from the left to the right, proceeding from the entrance to the reactor. The tube is represented as horizontal just for simplicity, and the temperature in the tube is shown on the y-axis.

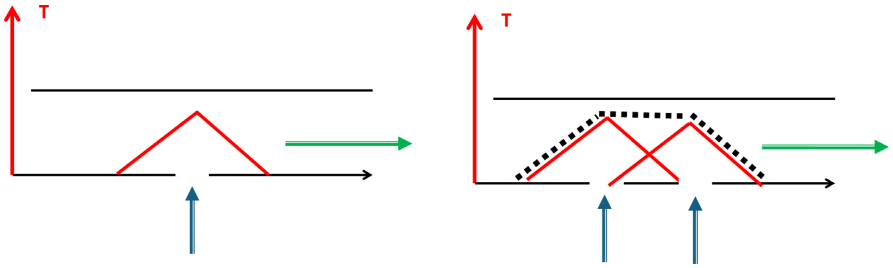

Figure 1. Sketch of a gasifier pipe where the biomass is moving from left to right (going toward the reactor), with its temperature reported on the y-axis. Left: the temperature profile is shown in the presence of just one inlet. One can assume that in correspondence with the air/oxygen inlet, the biomass will have a maximum temperature. The temperature is then lowered moving far away from the inlet. Right: temperature profile if a second inlet is added, under the simplifying hypothesis that the resulting profile is the sum of the profiles obtained with a single inlet.

In the left drawing, there is just one inlet for primary air: the material will increase its temperature when approaching this inlet, there will then be a maximum in the temperature distribution, and—as the material moves away from the inlet—the temperature will again decrease. Under the current paradigm, it would not be advisable to create an additional opening in the vicinity of the first one, rather one would add additional inlets at a large distance, such that different reaction zones result. However, if the airflow does not need to be limited, a second air inlet close to the first one can be added, so that their reaction zones overlap. For simplicity, it can be assumed that the resulting temperature is just the sum of the temperatures created by each single inlet, as shown in Figure 1 (on the right). This results in an extended region of high temperature. By adding additional inlets (not shown in the figure), the reaction zone can be extended to any length. Under the assumption that a gasifier power is a monotonically increasing function of the temperature, a reactor which is everywhere at the highest temperature allowed by the material, will have the highest possible power. The assumption that the temperature profile is a simple sum of individual inlets' contributions might be an oversimplification: detailed computational fluid dynamics simulations or experimental validation of the temperature distribution within the reactor will be performed in the future. The prototype resulting from these considerations is shown in Figure 2 (left).

It has a height of 150 cm and it is built out of 3 mm thick stainless steel. A transport screw brings the biomass from the hopper through the transport pipe (12 cm diameter) upwards to the gasification reactor. The reactor is a steel

container with about one hundred small inlets (3 mm). A detail of the gasifier design is shown in Figure 2 (right), and the main parameters are shown in Table 1.

Figure 2. Left: Prototype of the new gasifier for waste biomasses. Left: the actual device is shown (without the covering isolation material). The gasifier is 150 cm and is made out of 3 mm thick stainless steel. Right: Detail of the gasifier CAD design: in grey one can see the reactor with the air inlets, and in blue the carbon container. In red and green the two external chambers supply primary air to the reactor.

Table 1. Main parameters of the gasifier presented in this paper.

Material	Stainless steel (0.3 cm)
Insulator	Ceramic fiber (0.25 cm, 64 kg/m^3)
Gasifier height	150 cm
Gasifier width	80 cm
Reactor height	45 cm
Carbon container (hopper) height	45 cm
Reactor and hopper radius	23 - 35 cm
Reactor volume	5 l
Power	50 kW

The gasification reactor is 45 cm long, and it widens towards its upper end (to reduce the forces of friction between the material and the tube wall). The reactor has a volume of about five liters. As shown in Figure 2 (right), the distance between the inlets in the reactor wall is about 3 cm, resulting in one single reaction zone. To guarantee a constant temperature over a large part of the gasification volume, it would be necessary to supply each inlet or at least small groups of inlets with an adjustable airflow. In this prototype device, this is not possible, since it has only two separate sections where the airflow can be adjusted. These sections are created by two chambers with primary air around the tube (see Figure 2

(right)): the ideal situation of a large gasification volume with a constant temperature is just approximated. Since the material is moved from below to above, ash or impurities contained in the biomass and the fraction of biomass that has not been gasified, are automatically loaded into a "carbon container" (hopper) at the top of the device. The biomass container and the carbon container can be opened automatically to supply fresh biomass or to remove ash, respectively. The resulting syngas are mixed with a secondary airflow in an external burner outside the gasifier and are then burned. At the wall of the gasifier tube, there are four temperature sensors, positioned as shown in Figure 2 (left). Sensor 1 is the sensor in the lowest position (where the cold biomass enters the gasifier, while Sensor 4 is in the highest position). The temperature sensors are thermocouples type K, read by a Seneca electronics module able to create an output 0 - 10 V which is then read by a Siemens logo. The motor of the transport screw and the two motors controlling the opening and closure of the biomass and the ash containers are controlled by the same Siemens logo, which also reads the temperature sensors. Two Micronel ventilators supply the primary airflow.

The gasifier is equipped with a sensor that measures the biomass level in the reactor. This allows for two different kinds of operation:

- keeping the level of biomass constant—based on the information from the position sensor, one can gasify all or almost all of the biomass;
- supplying the material at a higher speed so that the partially gasified biomass will overflow the reactor and fall into the carbon container. This unprocessed material is effectively vegetal carbon. It could either be used in traditional combustion devices, reducing their emissions. Or it could be stored, to get an easy, cheap, and safe system of carbon sequestration.

3. Results and Discussion

The system was commissioned using wooden (conifers) pellets as combustible, to test the device and adjust the operation parameters. The reactor was kept full of biomass, without material overflowing to the carbon container. Figure 3 shows the temperature of each of the four sensors at intervals of about one minute. The figure shows that the gasifier requires approximately one hour to reach thermal equilibrium. The sensor which measures the lowest temperatures (Sensor 1 in Figure 2) is located where the biomass enters the reactor, and it is constantly at a temperature of approximately 500˚C. Higher up in the reactor the temperature increases and reaches 800˚C. This means that the tar cloud which is created by pyrolysis travels for approximately 45 cm through a carbon-rich environment at temperatures between 500˚C and 800˚C.

The data-taking lasted more than four hours and the gasifier consumed approximately 15 kg of pellets per hour, for an estimated thermal power of about 50 kW. About 55 - 60 kg of pellets have been gasified, and 0.5 kg of material was eventually found in the carbon container at the end of the test.

The reduction of CO_2 to CO, $CO_2 + C \rightleftharpoons 2CO$, which is an important process

when gasifying coke or high-quality coal, requires about 800˚C to produce CO (Boudouard equilibrium). This gasifier reaches this temperature and then these reactions must occur during the data taking. However, wood consists mostly of volatile materials that form a cloud of tar, visible when heating wood above 300˚C (in the absence of oxygen). Therefore one can assume that a large part of the gasification occurring in the reactor is from the reduction of tar (which may occur also at lower temperatures) rather than the reduction of CO_2 molecules.

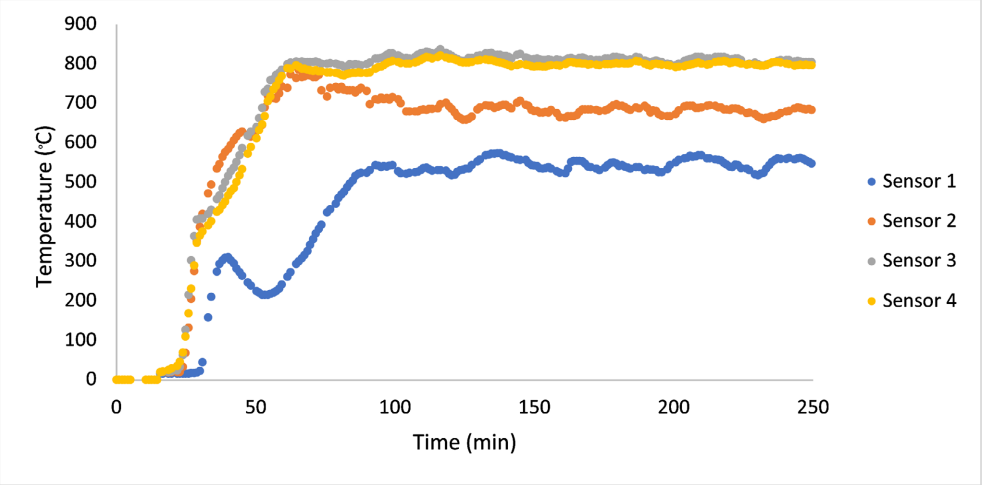

Figure 3. Temperature (˚C) vs time (minutes) distribution measured by the four sensors as obtained from the commissioning test of the gasifier working with wood pellets.

If these arguments are correct, it should then be possible to operate this gasifier also at lower temperatures, at which a conventional gasification process could not occur anymore.

To test this hypothesis the gasifier has been again operated using wood pellets (as done in **Figure 3**) but with a reduced flow of primary air. The results are shown in **Figure 4**: due to the reduced airflow, the temperature is now significantly lower. The material consumption turns out to be half of the previous experiment (**Figure 3**). Since the material moved more slowly into the reactor, the temperature profile is more even, with approximately 600˚C everywhere in the reactor after the thermal equilibrium has been reached.

Operating the gasifier at 600˚C opens a new perspective for the gasification of straw. Several previous studies showed that straw would be an excellent combustible [21] since it has about the same heat content as wood and is produced each year in large quantities. However, in contrast to wood, the ash of the straw already becomes liquid at a temperature between 600˚C to 700˚C. When it cools afterward it can become solid, possibly blocking the gasifier. A satisfying technical solution to this problem did not exist up to now to the best of our knowledge.

However, if one could gasify straw at 600˚C, the problem of ash melting can be avoided. Even better would be to go lower than 600˚C, to guarantee stable operations. The primary airflow was then further reduced and approximately 20 kg of

straw pellets were fed in the biomass container. The temperatures registered during this test are shown in Figure 5.

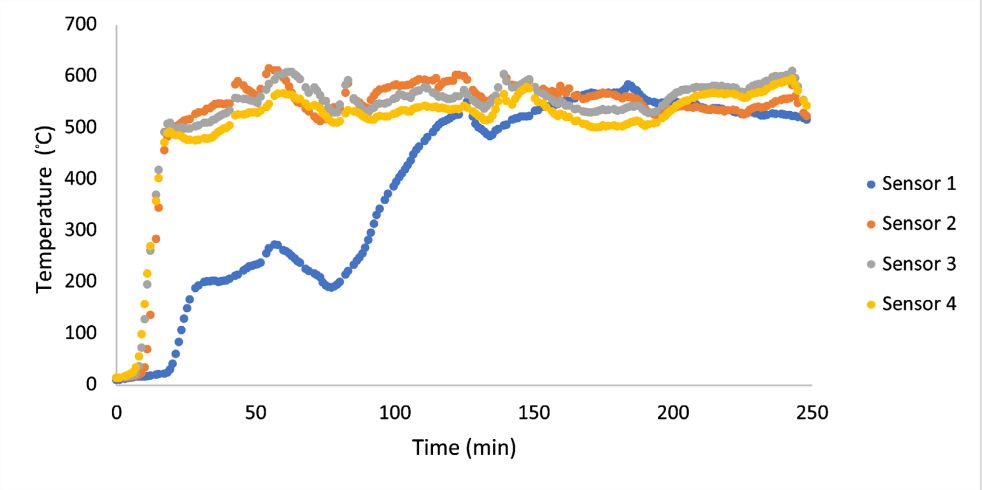

Figure 4. Temperature (˚C) vs time (minutes) distribution measured by the four sensors as obtained from the second test of the gasifier, still working with wood pellets but this time operated with a reduced flow of primary air. The temperature profile is now lower (at approximately 600˚C).

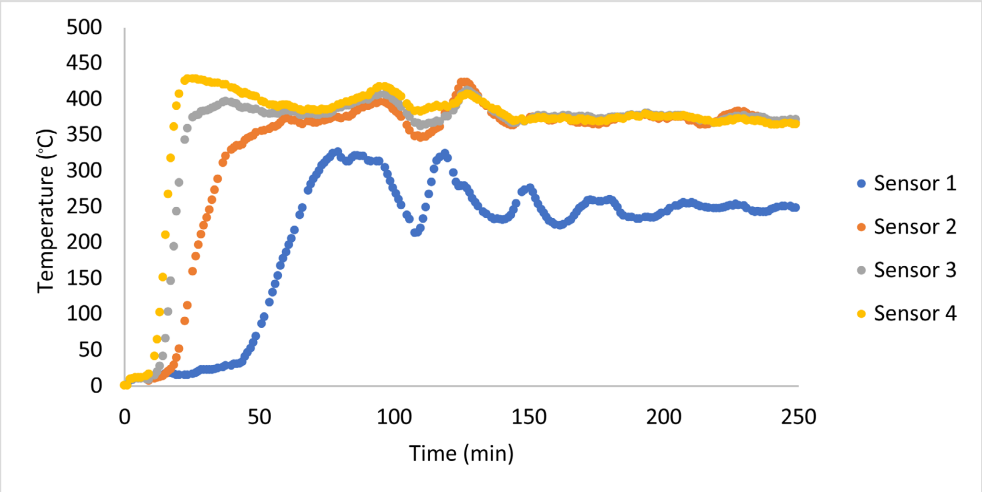

Figure 5. Temperature (˚C) vs time (minutes) distribution measured by the four sensors as obtained from a test of the gasifier working with straw pellets and with the temperatures controlled via the primary air flow.

The gasifier is now operating at 400˚C. It is clear, that the reactions occurring inside must be different from those inside a traditional gasifier with coal at 800˚C: a wide and very challenging field of future scientific studies seems to be opened here. Straw pellets have also been processed at high temperatures, to compare the results with previous studies: after about one hour the gasifier has reached 700˚C, arriving then at a peak of 800˚C. The gasification process slowly stopped and the temperature began to decrease constantly. After the device cooled down it was opened and as expected large blocks of sintered material were found which

blocked not only the material flow but also the primary air inlets. This is compatible with what was reported from previous experiments. The sintered material was then removed using a screwdriver, a simple operation made possible thanks to the extreme simplicity of the device—consisting only of a steel tube.

Another important resource of waste biomass is the green cut collected in the municipality. In the Friuli Venezia region (Italy) it is usually disposed of at a cost of about 100 Euro/ton, as if it were municipal waste. A typical town like Udine (around 10^5 inhabitants) produces an order of 10^4 tons of this material each year, its energy content corresponding to about 3×10^3 tons of heating oil or gas. The gardening team of the University of Udine provided material collected on-site, visible in Figure 6, which was only chopped, not pelletized, characterized by a humidity of 10%.

Figure 7 shows the temperature reached during the gasification of about 20 kg

Figure 6. Raw biomass collected and chopped by the University gardening team.

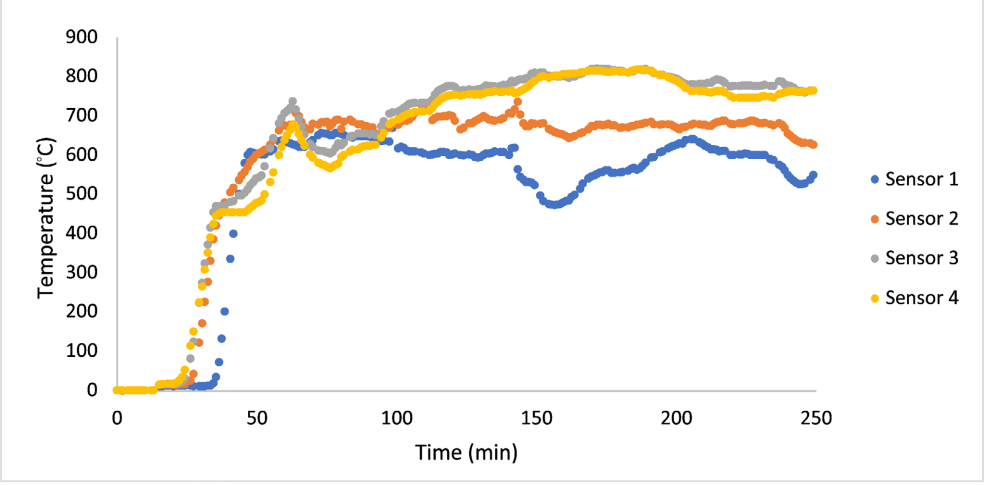

Figure 7. Temperature (˚C) vs time (minutes) distribution measured by the four sensors as obtained from a test of the gasifier working with chopped (not pelletized) green waste collected at the University site.

of this material. The lowest temperature sensor shows rather strong fluctuations, due to the uneven transport of the non-pelletized material in the screw. Despite these fluctuations, the green cut was gasified completely and without problems.

In an additional test, 45 kg of green cut was gasified at an increased transport velocity, so that a fraction of the material fell into the carbon container before being completely gasified. In this way, 14 kg of vegetal carbon was obtained. Since about 5 kg of material was consumed for the initial heating of the gasifier to operational temperature, one can conclude that 14 kg/40kg = 35% of the biomass was not gasified but transformed into biochar or vegetal carbon.

Gas Composition

The new features of this physics-based gasifier will lead to new applications and should guide many interesting scientific studies. Some very first measurements of the gas composition performed with an MRU VARIOluXX gas analyzer confirm this: during the gasification of wood pellets at a temperature of 400˚C the syngas contains 16% of CO, 12% of H_2 and 2% of CH_4, while the CO_2 content is 12% percent. At 700˚C the CO content increases to 18%, the H_2 content increases to 14%, the CO_2 to 13%, while the CH_4 content remains stable. These results are shown in Table 2.

Table 2. Syngas composition for two different temperatures as measured by the gas analyzer.

Gas	400˚C	700˚C
CO	16%	18%
CH_4	2%	2%
H_2	12%	14%
CO_2	12%	13%
N_2	55%	52%

This confirms that with this device gasification occurs already at 400˚C. Since the temperature increase is obtained from an increase of primary air, it also shows that gassification in the reactor does not turn into combustion under an increase of oxygen supply.

If one now provides (always at 700˚C) together with the primary air water steam with a power of 0.9 kW, the H_2 content increases to 16%, while the CO concentration falls to 15%.

During the injection of the water vapor, the temperature fell by about 50˚C in the lower part of the gasifier but increased by 50˚C in the upper part. These first and preliminary results motivate future more detailed experimental and theoretical studies, and suggest the possibility of producing hydrogen from waste biomass in a CO_2-neutral way. In the future, a wider range of operating conditions, feedstock variations, and long-term performance data will be crucial for a more robust validation of the device, together with a comparison of this high-flow gasifier with

the existing technologies.

4. Conclusion

The gasifier prototype—based on a physics-driven design—works very well. It is simple and compact, providing a power of about 50 kW from a reaction volume of only five liters, for a power density of 10 MW/m^3. This is comparable to the power densities of nuclear reactors, which are between 6 and 100 MW/m^3. It is even possible to gasify straw, which by some is considered the most difficult waste biomass for gasification due to its low ash melting temperature. In contrast to wood, which needs many years to grow, waste biomasses grow very fast. Therefore the gasifier has the potential to give an important contribution to reducing the CO_2 content of the atmosphere on a useful time scale. The gasifier can either completely gasify the biomass or gasify it partially, leaving vegetal carbon. This vegetal carbon can then be used, with few emissions, in traditional fireplaces which are not able to process waste biomass or it can be stored for simple and cheap carbon sequestration. This physics-based gasifier breaks a 180-year-old engineering paradigm, paving the road to much more simple and compact systems, showing thereby that physics also today can give important contributions to the solution of engineering problems. These first results are encouraging enough to justify more detailed studies which will be performed in the future.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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