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Pilot-scale gasification of woody biomass

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ABSTRACT

The gasification of pine and mixed-hardwood chips has been carried out in a pilot-scale system at a range of gas flow rates. Consuming ~17–30 kgh^{-1} of feedstock, the producer gas was composed of ~200 $dm^3\ m^{-3}$ carbon monoxide, 12 $dm^3\ m^{-3}$ carbon dioxide, 30 $dm^3\ m^{-3}$ methane and 190 $dm^3\ m^{-3}$ hydrogen, with an energy content of ~6 MJ m^{-3} for both feedstocks. It was found that the efficiency of the system was enhanced at higher flow rates.

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1. Introduction

The gasification of biomass has a long history, notably its application in Europe during World War II. Given the current economic, political and environmental issues associated with fossil fuels, such biomass-based thermochemical processes have once again begun to receive attention. This is evidenced by reviews in the literature [1–7].

There are, of course, several different types of gasifiers including updraft, downdraft and fluidized bed reactors. The objectives of the current work are concerned with the operation and performance of a pilot-scale, downdraft gasifier with different feedstocks and gas flow rates. In such a system the fuel, air and producer gas move together through the reactor, exiting at the bottom. Downdraft gasifiers are characterized by low production of tars, the need for a relatively low moisture content of the fuel and high temperatures of the gas as it exits the reactor, which in turn requires a secondary heat removal system [1].

Sheth and Babu [8] report on the use of a downdraft system for the gasification of wood-waste from furniture manufacture. It was found that fuel consumption decreased as the moisture content increased. The authors also found that as air flow increased, consumption increased, and char production generally decreased. The composition of the producer gas was ~200 $dm^3\ m^{-3}$ carbon monoxide, 100 $dm^3\ m^{-3}$ hydrogen, 70 $dm^3\ m^{-3}$ carbon dioxide, 20 $dm^3\ m^{-3}$ methane, with energy contents ranging from 4.5 to 6.5 MJ m^{-3}, depending on the equivalence ratio.

Working with a laboratory scale downdraft system, Skloulou et al. [9] have examined the gasification of cuttings and pits from olives. At temperatures of 750 °C–950 °C the authors report that gas production accounts for about 60% of the product, while char and tar represent ~10% and 30%, respectively. While high, the tar levels decrease at the highest temperature. The gas compositions varied over a fairly narrow range, as a function of temperature, with carbon dioxide at 500 $dm^3\ m^{-3}$, carbon monoxide ~200 $dm^3\ m^{-3}$,

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hydrogen ~250 dm^3 m^{-3}, and methane 80 dm^3 m^{-3}, with low levels of ethylene and ethane reported. Somewhat high values of 8-9MJm^{-3} are reported for the energy content of the gas.

Experimental and modelling results from downdraft gasification of red and white luan have been reported by Hsi et al. [10]. In this work the air flow rate was controlled while maintaining temperatures of 600–800 °C, depending on the location of the thermocouple within the gasifier. Lower air/fuel ratios resulted in higher heating values of the gas ranging from ~4.5–6 MJ m^{-3}. Carbon monoxide, carbon dioxide and methane levels were reasonably uniform across flow rates at about 180, 100 and 15 dm^3 m^{-3}, respectively. The amount of hydrogen produced was much more variable, ranging from ~11–19 dm^3 m^{-3}.

Zainal et al. [11] have gasified furniture waste and wood chips at temperatures of about 800 °C, at equivalence ratios of about 0.25–0.45. Carbon monoxide, methane, and the energy of the gas all exhibit maxima at an equivalence ratio of ~0.35, while carbon dioxide shows a corresponding minimum. Hydrogen levels increase monotonically with equivalence ratio.

Working with hazelnut shells, Dogru et al. [12] over a narrow range of air/fuel ratios have produced gas with heating values of aproximately 3.5 to 5.15 MJ m^{-3}. As was reported by Hsi et al. [10] lower air/fuel ratios resulted in higher energy contents of the gas.

In a series of papers Geyer and Walawender and co-workers have reported on the downdraft gasification of several different species of wood [13–16]. All work was done with a bench-scale fluidized bed gasification unit. A study of *Populus* clones showed no differences in gasification results with clone, but with high energy contents of the gas, reported at about 13MJm^{-3} [13]. The gas compositions were also quite similar for the clones tested at ~350 dm^3 m^{-3} hydrogen, 260 dm^3 m^{-3} carbon dioxide, 250 dm^3 m^{-3} carbon monoxide, and 80 dm^3 m^{-3} methane. In analogous work on catalpa the gas heating value ranged from 4.82 to 5.15 MJ m^{-3}, while the hydrogen composition was 109–129 dm^3 m^{-3}, carbon dioxide 134-152 dm^3 m^{-3}, and carbon monoxide 222-272 dm^3 m^{-3} [14].A study of several hardwood species (cottonwood, black locust, oak, silver maple and deteriorated silver maple) showed that the air/fuel ratio was important in determining the energy content of the gas, which ranged from 5.55 to 6.22 MJ m^{-3} [15]. Relatively low variability is observed for gas composition with species. Finally, Siberian elm [16] gasified at temperatures of 600–700 °C is reported to produce gas with heating values of ~11–12 MJm^{-3}. As was seen in the *Populus* work [13] the hydrogen percentage was quite high, 442 dm^3 m^{-3}, probably accounting for the elevated energy of the gas.

Work has also been reported for downdraft gasifiers very similar to the unit used in the current research by Diebold et al. [17] and Wei et al. [18]. In the latter paper, hardwood chips with moisture contents of 10–19% were gasified with an exit temperature of 750–950 °C and gas flow rates of 35–55 m^3h^{-1}. Moisture content was found to exert a negative influence on the carbon monoxide percentage and heating value of the gas, while increasing tar collection. The energy content of the gas ranged from 5.5 to 6 MJm^{-3}, while the carbon monoxide percentage was 200–240 dm^3 m^{-3}, hydrogen ~180 dm^3 m^{-3}, carbon dioxide 120 dm^3 m^{-3} and methane 40 dm^3 m^{-3}.

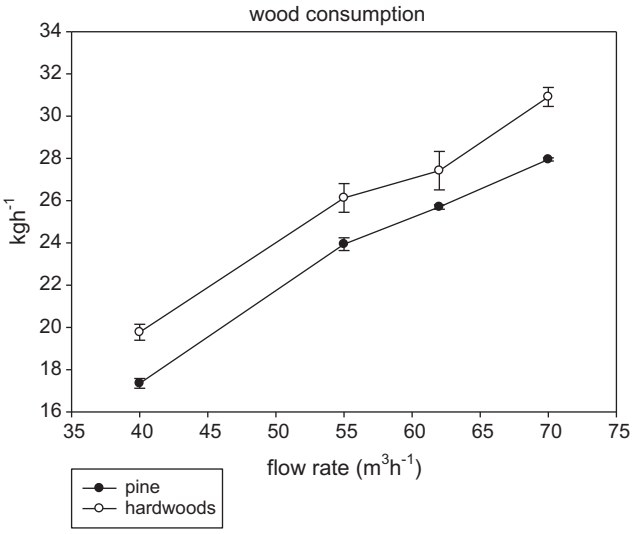

Fig. 1 – Wood consumption rates as a function of gas flow rate.

The objectives of the current work are to determine the effect of feedstock type and process conditions on the composition and quality of producer gas from a pilot-scale gasification unit.

2. Methods and Materials

The feedstocks used in the current work were chips from a commercial supplier in central Louisiana. After delivery to the chipping facility, the logs are kept under water spray to retard decay. The samples consisted of southern pine (a mixture of loblolly (*Pinus taeda*), longleaf (*Pinus palustris*) and shortleaf (*Pinus echinata*) pines) and mixed-hardwood ~50% oak (*Quercus* spp.), 25% elm/hickory (*Ulmus/Carya* spp.), 25% sweetgum/maple (*Liquidambar styraciflua/Acer* spp.). Wet chips were pre-dried to approximately 15% moisture content (dry basis).

All gasification runs were performed using a Biomax 25 manufactured by Community Power Corporation in Littleton, Colorado. The unit includes drying/storage bins with capacities of about 250 kg, a conveyor for distribution of the chips onto a vibratory size classifier, and a screw-auger for transport of the chips into the gasifier. The gasifier is cylindrical with a diameter of 35.6 cm and length 118.3 cm with five thermocouples and secondary air inlets to control the temperature of the reaction located at 20.2, 35.3, 46.8, 60.2 and 73.5 cm from the bottom. The unit operates continuously and is open to the atmosphere. The feedstock is initially ignited by a resistance heater and the downdraft is created by a roots blower. In this work, the flow rates were set at 40, 55, 62, and 70 m^3h^{-1} (where a m^3 is defined at 0 °C and 101.3 kPa), with duplicate runs performed for each feedstock and flow rate. The producer gas

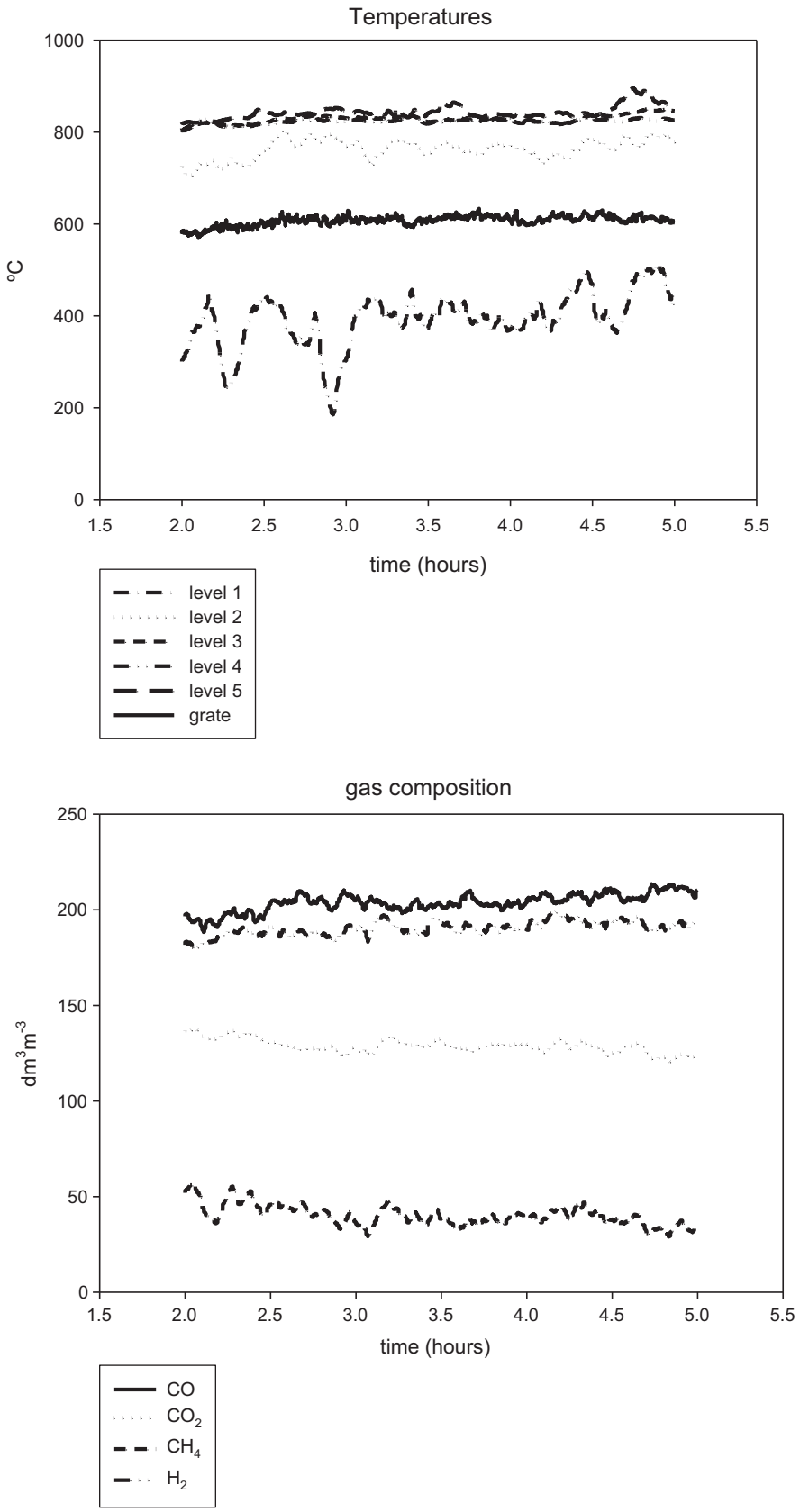

Fig. 2 – Typical profiles for temperatures and gas compositions for a 3 h data collection period.

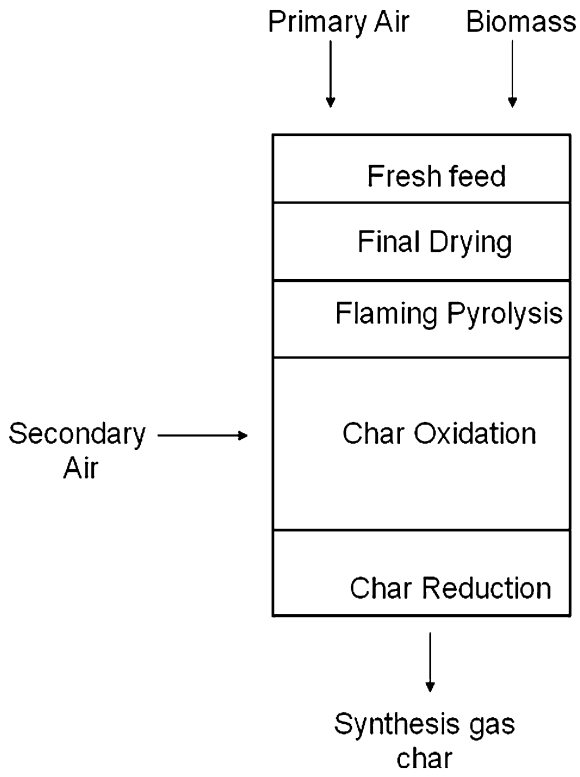

Fig. 3 – Thermal processes within the gasifier.

exits the gasifier at a temperature of about 500 °C and undergoes secondary cooling to a temperature of about 110 °C with an air cooled, shell and tube heat exchanger. The cooled gas is filtered to remove particulates, and analyzed in real time for oxygen, carbon monoxide, carbon dioxide, hydrogen and methane using a Nova 7900P5 infrared gas analyzer. The resultant gas is subsequently flared off. Individual runs involved approximately an hour to reach gasification conditions, an hour to allow the system to equilibrate and 3 h of data collection. In addition to gas composition, data collected includes the amount of material consumed, energy content of the gas, and efficiency of the process as calculated by in equation. 1.

$$\eta = \left(\text{energy content of gas produced}\left(\text{MJkg}^{-1}\right)\right) \Big/ \left(\text{fuel input (kg)}\right) \Big/ \text{energy content of 1kg fuel}\left(\text{MJ}\right) \text{[7]} \quad (1)$$

3. Results and discussion

All results will be taken from the final 3 h data collection as specified in the Methods and Materials section.

Fig. 1 shows the consumption of feedstock on an hourly basis, as a function of flow rate. Fig. 2 shows the temperatures and gas compositions for a typical 3 h data collection period. It can be seen that the feedstock consumption increases with flow rate in a generally linear manner, and that the consumption of hardwoods has a higher degree of variability and is somewhat greater than for pine, probably due to higher density. The temperatures within the gasifier during a 3 h period show that level 1 exhibits a lower temperature and more variability due to its proximity to the top of the unit. Otherwise, the temperature ranges are fairly narrow, especially for levels 3, 4 and 5. The grate is at the bottom of the unit and it can be seen that the gas is already beginning to cool as it exits the gasifier. The gas composition values (Fig. 2) also indicates that variability is low over the course of the 3 h data collection period. Fig. 3 illustrates the continuum of thermal processes that are occurring at the various levels of the gasifier. While these may vary with the properties of the feedstock and the flame front, which is under computer control, level 1 may be assigned to the pyrolysis zone, with level 2 perhaps corresponding to late pyrolysis or the initial stages of oxidation. Levels 3 and 4 would, therefore be associated with oxidation, with reduction occurring between level 5 and the grate.

Fig. 4 shows the temperatures at the various levels of the gasifier as a function of flow rate. In general the temperatures increase with flow rate, and throughout the temperatures associated with gasification of the pine are higher than for hardwoods, probably due to the presence of extractives in the former. It is also interesting to note that the temperatures for pine remain reasonably constant with flow rate, while the temperatures within the gasifier at the lowest flow rate are markedly lower for the hardwoods. As the gas proceeds through the system, however, the temperatures associated with hardwoods becomes more uniform even at the low flow rates. The level 1 temperatures, associated with the pyrolysis zone, are most apparent in this regard and may be interpreted as a lowering of the flame front within the gasifier for hardwoods at the lowest flowrate [17]. It can also be seen that, in agreement with Fig. 2, the variability in levels 3 and 4, as evidenced by the error bars is quite low. Upon exiting the heated zone and entering the grate the temperature decreases rapidly, due to the endothermicity of the reduction reactions, and for both pine and hardwoods is measurably lower at 40 m^3h^{-1}.

The changes in composition of the producer gas, energy content and efficiency with flow rate are as shown in Fig. 5. An examination of the scales will reveal that as was seen in Fig. 1, the gas composition values exhibit a very narrow range of variability and, with the exception of carbon dioxide, overlap between pine and hardwoods. The degree of overlap, notwithstanding, carbon monoxide is generally higher in the pine, while as would be expected from this result, carbon dioxide is higher for the mixed-hardwoods. Furthermore, hardwoods produce higher levels of both methane and hydrogen, although the differences in the former are very slight. The overall gas composition in the current work is in general agreement with the results reported in the literature [17,18].

The energy content of the producer gas (in MJm^{-3}), as a function of flow rate (Fig. 5), indicates that there is considerable overlap between the feedstocks, with the results at 40 and 55 Nm^3hr^{-1} virtually identical. At the higher flow rates, the hardwoods level off, and there is a slight decrease at 70 m^3h^{-1} for the pine. As before, the variability with flow rate is rather small, although from these the results the highest energy content occurs at the lowest flow rate. The pattern of

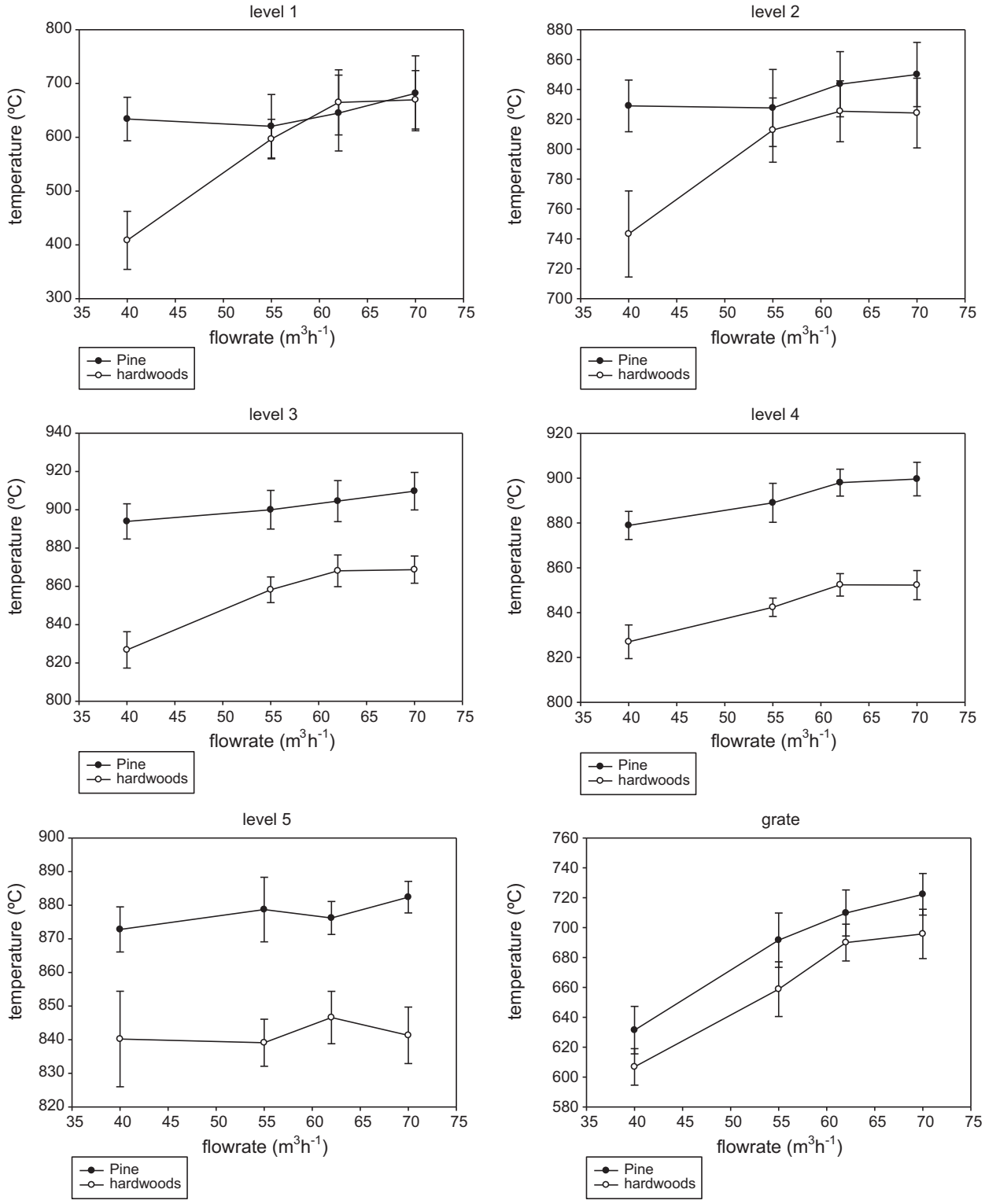

Fig. 4 – Temperatures within the gasifier for each feedstock as a function of gas flow rate.

these results is not dissimilar to the methane content of the gas with flow rate (Fig. 5). The efficiency results (Fig. 5) are striking, with a marked increase at the higher flow rates, perhaps indicating that there would be advantages in working under these conditions.

In summary, based on the composition and energy content of the gas produced, pine and hardwood chips give very similar results, most of which are within a standard deviation of each other, with slight differences due to changes in flow rate. In contrast, flow rate appears to exert a marked influence on the

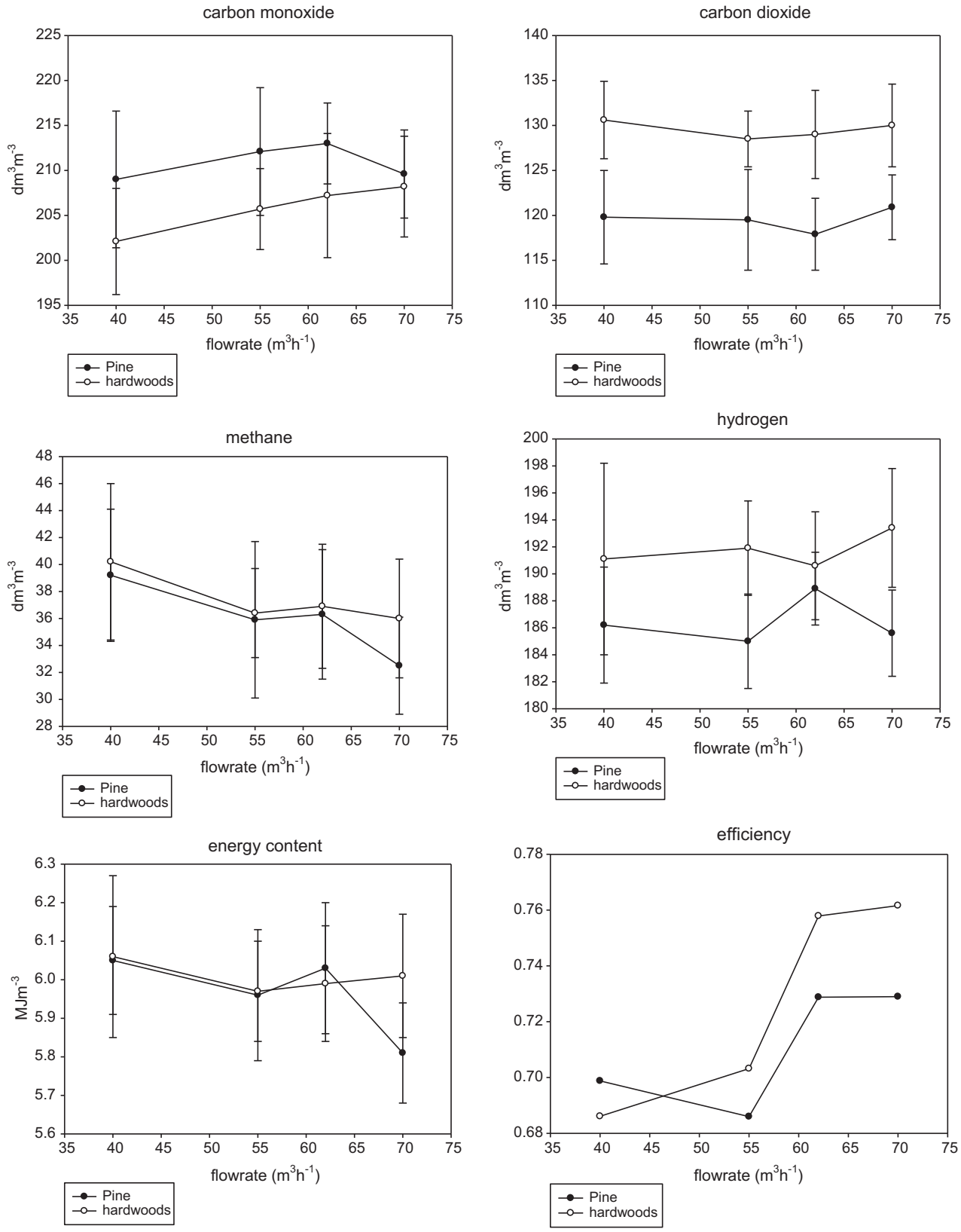

Fig. 5 – Producer gas composition, energy content and efficiency for each feedstock as a function of gas flow rate.

efficiency of the process, with the higher flow rates exhibiting higher values. The former results are consistent with previous observations on gasification. The process can effectively convert many different feedstocks with varying compositions to producer gas with reasonably uniform properties.

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