Sustainable valorisation of tyre crumb via microwave-induced plasma gasification

Joshua Chooyin, Amos Dexter, Long Duong, Basudeb Saha*, Andrew Steventon

School of Engineering, Lancaster University, Lancaster, LA1 4YW, UK.

*Corresponding author

E-mail address: b.saha@lancaster.ac.uk

Abstract

This paper investigates the thermodynamics of tyre crumb gasification using microwave-induced plasmas. Previous studies at Lancaster University explored plasma torch systems for the gasification of wood chips; however, the broader adoption of microwave (MW) plasma torch technology has been constrained by challenges in scaling up reactor systems. To address this limitation, the current project at Lancaster University has developed a novel applicator design capable of generating relatively stable MW plasmas within larger-diameter steel chambers. This innovative approach removes the reliance on traditional ceramic components typically required in plasma torches, thereby improving robustness and scalability. Tyre crumb has been selected as one of the trial feedstocks for this novel applicator, providing a valuable case study for assessing both the thermodynamic performance and the potential of MW plasma technology in advancing sustainable waste-to-energy processes.

Keywords

Microwave plasma; Advanced gasification; Sustainable valorisation; Tyre crumb; Process modelling.

Introduction

The UN recognises that progress must be made to achieve a more sustainable world [1]. Progress towards their goals can be achieved through better use of resources and improved management of waste. The global tyre industry is estimated to produce 3.66 billion tyres each year [2], and hence their disposal is a significant sustainability issue. In this paper, gasification as a disposal method is considered.

The authors are currently developing a novel microwave-induced plasma furnace where a mode converter is employed to keep the plasma away from the vessel walls. This enhances efficiency and alleviates the need for any ceramic components. Tyre crumb is one of the selected feedstocks for experimental trials. Whilst road vehicle pneumatic tyres are generally safe to handle, their combustion products can be highly toxic [3]. The combustion of tyres may release 10–100 times more polycyclic aromatic hydrocarbons (PAHs) than coal [4]. In contrast, gasification offers a more environmentally sustainable alternative. Literature reports indicate that tyre gasification can achieve 60–70% cold gas efficiency with 98–99% carbon conversion [5], while simulation studies suggest that efficiencies of up to 74% are possible [6].

A notable advantage of microwave-induced plasma gasification, compared with conventional combustion or thermal gasification processes that rely on the feedstock as the energy source, is its enhanced destruction of organic compounds. This results in an inert ash with negligible fixed carbon content [5] and significantly reduced emissions of volatile organic compounds (VOCs). In general, gasification involves the partial oxidation of organic materials to produce synthesis gas (syngas), primarily composed of carbon monoxide and hydrogen. The syngas can subsequently serve as a feedstock for chemical synthesis or as a fuel for electricity generation, for example, through a combined cycle gas turbine (CCGT) system [7].

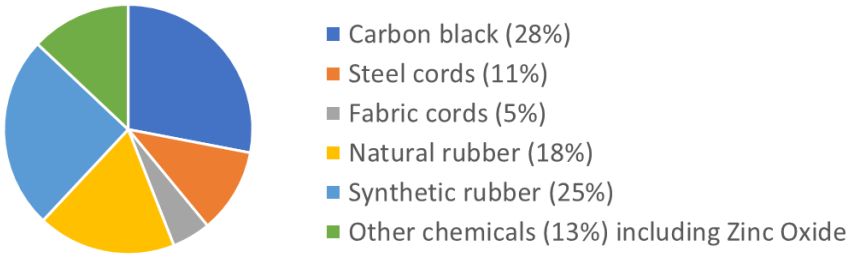
Gasification processes are usually exothermic at low temperatures but not sufficiently so to achieve the ideal temperature for fully effective gasification. By using a microwave plasma to supplement the supply of heat, gasification can be performed at an optimum temperature for maximum conversion of carbon. Temperature can be controlled independently of the amount of oxygen or air supplied. Optimising the supply of oxygen by the addition of either pure oxygen, air, or steam minimises unwanted carbon dioxide in the syngas. This optimisation is only possible with supplementary heating. The added energy will contribute to the calorific value of the syngas produced and hence does not

necessarily make the process uneconomic. For microwave-induced plasma gasification to be economically viable, the efficiency of microwave generation and the applicator are critical. The Lancaster project aims to increase the efficiency of the applicator by eliminating the need for supplementary cooling.

Tyre disposal and composition

Tyres are, by design, robust and non-degradable, with much of the developed world using strict legislation requiring periodic replacement or after a certain wear [8]. An effect of this is that over 81% of a tyre by weight remains as a waste product at the end-of-life tyre [9]. Some tyres might be re-treaded; however, most have their metal content removed and are then shredded into crumb [10, 11].

Crumb rubber from end-of-life tyres is often disposed of through incineration or pyrolysis. However, tyre pyrolysis can undesirably generate up to 3.5% by weight of polycyclic aromatic hydrocarbons (PAHs) [12]. Currently, tyre crumb is also used as infill material on sports pitches and playgrounds, though this practice is expected to be banned across the EU/EEA in the near future due to concerns regarding microplastic release and toxic emissions [13]. Although tyre formulations vary among manufacturers, their overall composition is sufficiently similar for comparative assessment. The representative composition shown in Figure 1 provides a useful basis for evaluating the suitability of tyres for bulk combustion, pyrolysis, or gasification. Proximate and ultimate analyses, as reported in [11] and summarised in Tables 1 and 2, are particularly relevant for understanding plasma behaviour and downstream processing requirements. The nitrogen content has the potential to form nitrogen oxides (NO_x), while sulphur may be released as sulphur dioxide (SO_2) or hydrogen sulphide (H_2S). Consequently, the cost of syngas cleaning must be incorporated into any economic analysis. Furthermore, the presence of ash indicates that particulate filtration will be necessary in the gas cleanup system.



Source: https://www.resourcewise.com/blog/chemicals-blog/automotive-tires-for-a-sustainable-world

Figure 1 *Average tyre composition data taken from*

Table 1 *Proximate analysis of waste tyre crumb from literature [11]*

Volatile wt %	Fixed carbon wt %	Moisture wt %	Ash wt %	HHV MJ/kg
67.3	28.5	0.5	3.7	25.1
64.97	30.08	0.75	4.16	38.6
62.32	26.66	1.31	10.29	-
61.9	29.2	0.7	8.0	-
66.5	30.3	0.8	2.4	40
68.7	23.3	0.4	7.6	-
62.2	29.4	7.1	1.3	40

Table 2 *Ultimate analysis of tyre crumb according to literature [11]*

C wt.%	H wt.%	N wt.%	O wt.%	S wt.%	Ash wt.%
83.8	7.6	0.4	3.1	1.4	3.7
83.92	6.83	0.78	3.39	0.92	4.16
74.41	6.94	0.21	5.02	1.60	10.21
86.7	8.1	0.4	1.3	1.4	2.1
85.9	8.0	0.4	2.3	1.0	2.4

81.3	7.3	0.3	1.4	1.5	8.2
86.4	8.0	0.5	3.4	1.7	2.4

Chemical equilibrium of a stoichiometric mixture for gasification

Calculating the average ratio of hydrogen atoms to carbon atoms in Table 2 gives the ratio 25:23. Equations (1) and (2) give stoichiometric reactions for complete gasification with oxygen and steam, respectively.

$$23\ C + 12.5\ H_2 + 11.5\ O_2 \rightarrow 23\ CO + 12.5\ H_2 + 2.541\ MJ/mol \quad (1)$$

$$23\ C + 12.5\ H_2 + 23\ H_2O \rightarrow 23\ CO + 35.5\ H_2 - 3.020\ MJ/mol \quad (2)$$

Gasification in pure oxygen is likely to be more expensive as it must be produced. Gasification in steam produces a lot more hydrogen, but it is endothermic; hence, the microwave energy required is large. Gasification in air will give 3.73 times the oxygen input as nitrogen in the output, which for equation (1) becomes,

$$23\ C + 12.5\ H_2 + 11.5\ O_2 + 43\ N_2 \rightarrow 23\ CO + 12.5\ H_2 + 43\ N_2 \quad (3)$$

Some gas turbines can run efficiently with nitrogen dilution; however, one might choose to optimise the ratio of steam to air to give a fuel that does not compromise gas turbine efficiency. There is a small amount of nitrogen in the tyre crumb, hence the nitrogen content in the final syngas will never be zero. During the gasification process, oxides of nitrogen and hydrogen cyanide might also be produced. Temperatures should be chosen to minimise unwanted emissions.

It is of interest to undertake a chemical equilibrium analysis of a mixture of nitrogen, carbon, oxygen and hydrogen as a function of temperature up to the highest temperature expected to be present in the plasma. A Gibbs free energy minimisation is performed with our own code using the JANAF thermodynamic tables. For simplicity, the sulphur content is omitted at this stage. It will be considered in a later section when the computer code ASPEN Plus is used. Specifically consider,

$$23\ C + 12.5\ H_2 + 5\ O_2 + 13\ H_2O + 19\ N_2 \rightarrow 23\ CO + 25.5\ H_2 + 19\ N_2 - 0.602\ MJ/mol \quad (4)$$

Hence, the elemental input to our equilibrium calculation is 23 C, 51 H, 23 O, 38 N. In our simulation, consider the following gaseous output species (O, H, C, O_2, H_2, CO, CO_2, OH, H_2O, C_2, C_2O, C_3, CH_4, CH, N_2, N, NO, N_2O, NO_2, H_3N, HCN) are considered. Ionised species are not included. Solid carbon is not considered as an output species, as the supply of oxygen and hydrogen is sufficient for it all to react to the gas phase or evaporate. Gaseous carbon is included up to C_3 as C_2 (Swan bands), and C_3 are seen in the spectra from our type of plasma. Hydrocarbons heavier than methane are not included, as after gasification their concentration is much less than methane. The results are shown in Figure 2.

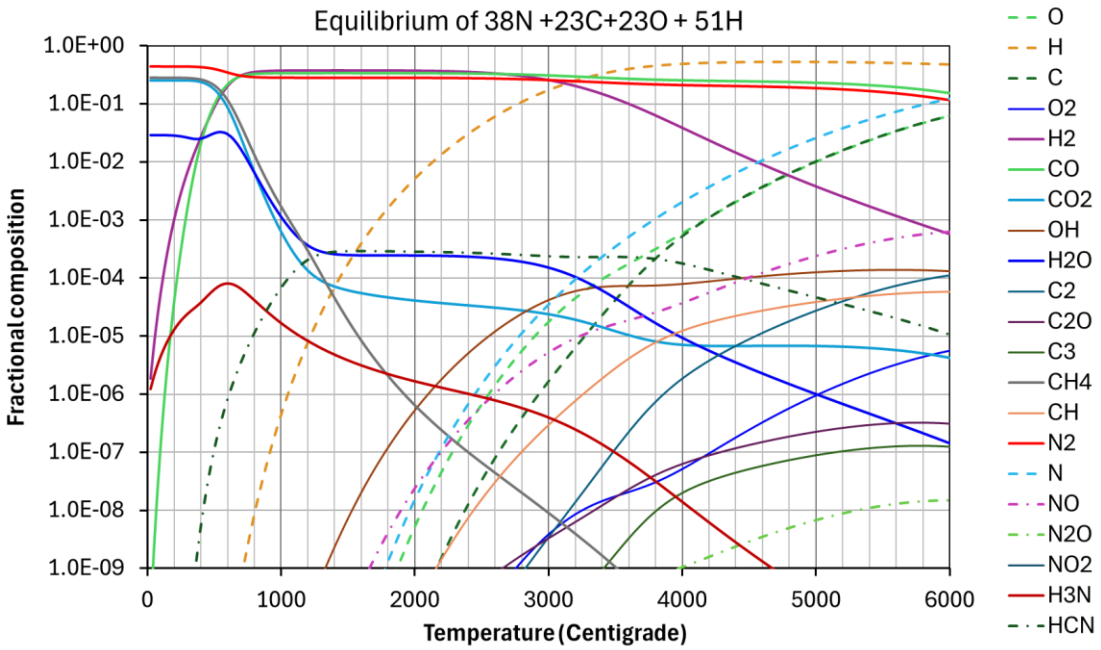


Figure 2 *Gibbs equilibrium of the carbon and hydrogen content of tyre crumb plus steam and air in a proportion that allows complete gasification*

Lancaster University has previously measured molecular vibrational temperatures of C_2 near 5900 °C in an atmospheric pressure, microwave-induced plasma with a carbon dioxide feed to a Sairem plasma torch, for a power input of 1.0 kW and a flow rate of 20 SLPM. It is for this reason that the temperature span in Figure 2 is extended to 6000 °C.

The plasma is not expected to be in thermal equilibrium. The microwaves only transfer significant amounts of energy to the electrons. The electrons are very much lighter than the molecules and atoms, hence they transfer very little energy by elastic collisions. In a molecular gas, the electrons gain energy and hence temperature until they excite molecular vibration. This limits the average electron energy to about 2eV (24,000 K); however, the tip of their Boltzmann distribution will be much higher. Electrons cannot easily reach ionisation energies at the power densities applied and for atmospheric pressure, unless gas temperatures are well above 5000 °C. The translational temperature for molecules is expected to be slightly less than the vibrational temperature. Temperatures are expected to vary with microwave power, gas flow rate and the gas feed; however, there will always be a very hot region where the temperature is above 5000 °C. Only a small fraction of the gas flow into the plasma gets heated to this temperature. By simple consideration of power input, flow rate and the equilibrium constitution as a function of temperature, the average temperature for gases leaving typical plasmas that this project runs is in the range 1500 °C to 2500 °C.

Figure 2 indicates that at room temperature, the lowest energy state is for the oxygen to be bound as carbon dioxide, and surplus carbon will form hydrocarbons. A small fraction of the oxygen will form water rather than carbon dioxide. Between 400 °C and 600 °C, the number of moles of gas is increasing, which is why the fractional concentration of nitrogen reduces. The fraction of CO passes 0.1% at 300 °C. The plateau for the production of CO and H_2 is between 1000 °C and 2000 °C above which molecular hydrogen starts to dissociate. Production of HCN is significant at gasification temperatures. It could rise to 30 ppm at 900 °C, 68 ppm at 1000 °C and has a plateau at 1450 °C of 290 ppm. To minimise HCN production, one might choose not to pass the tyre crumb through the hottest part of the plasma but rather use the downstream hot gases from the plasma to heat the tyre crumb. Figure 2 suggests there is no reason to attempt to gasify at temperatures above 1000 °C. The literature suggests that gasification temperatures (i.e. the feedstock temperature) above 900 °C are sufficient for the complete removal of solid/fixed carbon when sufficient oxygen is present.

Production of the oxides of nitrogen becomes significant above 3000 °C. If gases passing through the hottest part of the plasma are there for a short time, then cool quickly to 2000 °C and afterwards stay

close to this temperature as they heat the tyre crumb, oxides of nitrogen might reduce to acceptable levels as the equilibrium concentration at 2000 °C is 0.023 ppm (~23 μg/m^3).

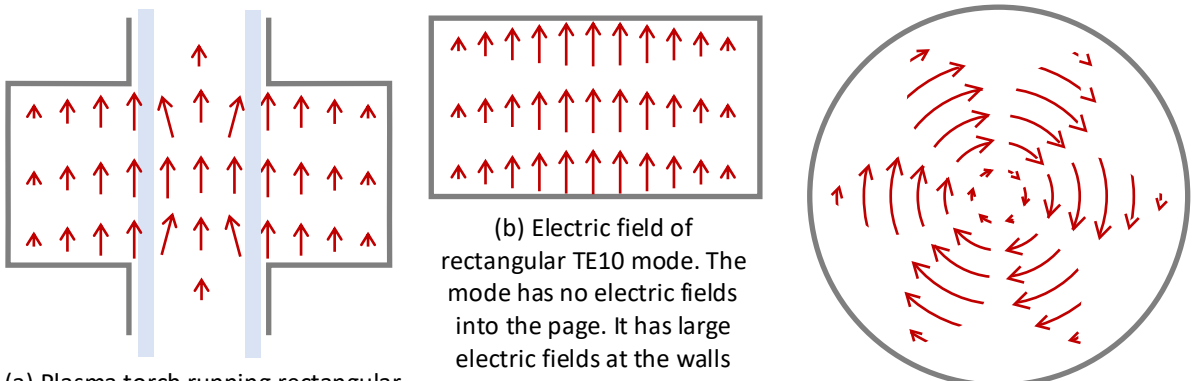
On this basis, the test rig has been specifically designed to channel the hot gases generated within the plasma vessel directly over a packed bed of tyre crumb. This configuration enables immediate thermal interaction between the plasma exhaust and the feedstock, thereby maximising energy transfer and facilitating effective gasification under controlled conditions.

Previous studies and the benefits of the new technology

Previous work on gasification at Lancaster University [14, 15] used a 2.45 GHz, 6 kW, microwave-induced plasma torch, supplied by Sairem SAS, Lyon, France. Atmospheric pressure, microwave plasmas are most easily excited within ceramic vessels that are themselves within microwave cavities or waveguides [16]. The ceramic vessel must be transparent to microwaves and be electrically insulating. The ceramic vessel is not essential, but it restricts the loss of electrons from the plasma, allowing the plasma to be run at lower power levels. If the vessel is a tube with a gas flow, then the plasma source is often referred to as a plasma torch.

The body of the Sairem plasma torch is formed by a fused silica tube, internal diameter 25.4 mm, passing through an aluminium rectangular waveguide WR340 (86.4 mm by 43.2 mm) and supporting the TE10 microwave mode. For this mode, the electric field is unidirectional and perpendicular to the wide face. The tube passes through the waveguide in the direction of the electric field. Microwave leakage is prevented by metal tubes (chokes) concentric to the fused silica tube, outside the waveguide and joining to the top and the bottom of the waveguide. These tubes have an internal diameter of 32 mm, which is too small for the propagation of microwaves at 2.45 GHz in any mode, in the absence of plasma. The plasma is initiated from an arc by briefly inserting a tungsten spike. The electric field in cross-section for the plasma torch is shown in Figure 3a, and for a rectangular waveguide without a tube in Figure 3b. Gas flow through the fused silica tube projects a plasma flame beyond the tube. The fused silica tube needs intense cooling to prevent it from melting or re-crystallising, and this makes the system inefficient. The plasma is strongly absorbing; hence, microwaves do not leak as a TEM mode along the cylindrical chokes once the plasma provides a central conductor.

The new applicator was conceived to increase the plasma volume, allowing scale-up and to eliminate the fused silica tube, which requires cooling and hence is an inefficiency. The concept was to operate in the TE01 waveguide mode of a cylindrical waveguide. This mode is very different to the TE01 rectangular mode as shown in Figure 3c. For this mode, the electric field circles around the axis. This mode has very low electric fields at the walls, and hence a plasma in the waveguide loses far fewer electrons and less heat to the walls. This increases thermal efficiency.



(a) Plasma torch running rectangular TE10 mode with cut-off cylindrical ports and a quartz tube shown in blue

(b) Electric field of rectangular TE10 mode. The mode has no electric fields into the page. It has large electric fields at the walls hence plasma heating at the walls

(c) Electric field of cylindrical TE01 mode has no electric field into the page or anywhere near the walls

Figure 3 *Electric fields on cross section in (a) a plasma torch, (b) a standard rectangular waveguide, (c) the cylindrical TE01 mode of cylindrical waveguide.*

For operation at 2.45 GHz, the diameter of the cylinder can be in the range of about 160 mm to 220 mm. A suitable mode converter was designed and manufactured for a diameter of 182 mm. The plasma only runs stably for a relatively small range of gas flows at powers above a specific threshold. An issue with operating at 2.45 GHz is that the best magnetrons are only 75% efficient. The design will simply scale from 2.45 GHz to 915 MHz, where magnetron efficiencies over 90% are possible, for instance, the 300kW CWM-300L developed by the California tube company [17]. This scaling increases dimensions by a factor of 2.67 and power handling by an order of magnitude. This makes industrial-scale processing plausible.

To optimise the gasification process, there is a requirement to vary the flow independently of power. This can be achieved by recirculating hot gases through the plasma, allowing higher flow rates at lower powers.

ASPEN Plus simulation of the gasification of tyre crumb

The current test bed is composed of three components: the microwave plasma chamber, the gasification furnace and the recirculation system. The chemical engineering software ASPEN Plus can model the gasification element of our process. It can also balance heat flow and enthalpy. The analysis given in this section uses the constitution for the tyre crumb given in row 5 in Tables 1 and 2 above.

For the calculation of Figure 2, constant temperature and pressure were assumed (Gibbs minimisation from the atomic constituents). Within our gasification chamber, after the plasma chamber, the process is better approximated as an adiabatic process. Following [18], we use a hybrid model for gasification as shown in Figure 4, but adapting it to our situation. This reference divides the processes that occur experimentally in the gasification chamber into three stages. In both Figures 4 and 5, the three stages, which experimentally constitute a single reactor, are enclosed by a dotted line. The first stage evaporates moisture and is labelled as drying. The drying temperature is set at 105 °C. The second stage is a pyrolysis reaction modelled with an RYield block with an input temperature set at 500 °C. The third stage is the gasification reaction modelled with an RGibbs block. The input temperature for this is not set. Net heat for drying and pyrolysis is taken from the plasma exhaust stream. The final temperature of products from the RGibbs block in the gasifier depends on the heat of reaction that occurred and the heat that was available in the exhaust stream from the plasma. Within an RGibbs reactor, one can compute chemical equilibrium at constant pressure for either constant temperature or constant enthalpy. The calculations of this section assume constant enthalpy and vary the airflow to the furnace (rather than a true Gibbs minimisation), hence the exhaust gases can gain or lose temperature.

Figure 4 shows the process diagram when there is no recirculation of syngas. Air enters the plasma chamber, and a heating block adds heat. This heating is coming from the microwaves. The air can partly dissociate and form Nitrogen Oxide; hence, a Gibbs block was added after heating. All the exhaust from the plasma chamber is taken to the gasifier.

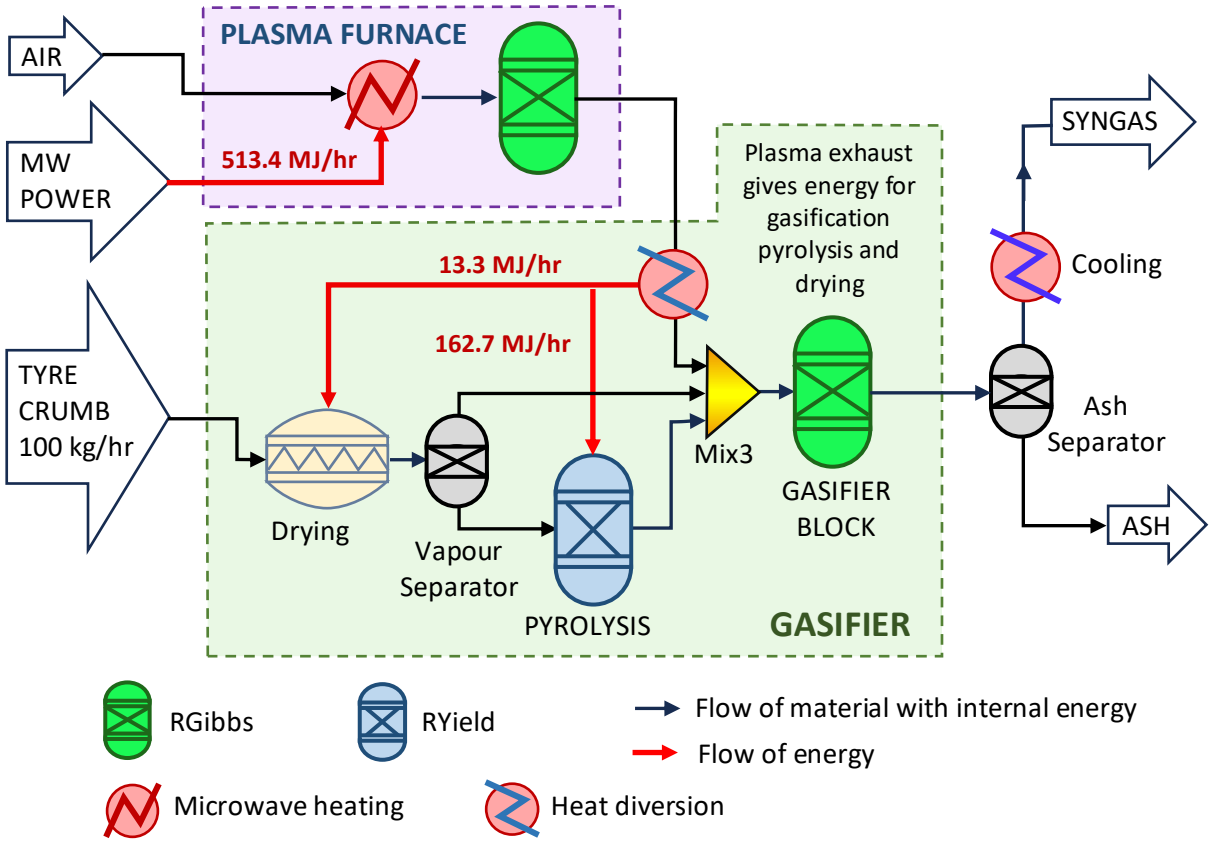


Figure 4 *Process flow diagram used for ASPEN Plus simulation without recirculation*

Figure 5 shows the process with recirculation. This situation is more complex as the feed to the plasma chamber includes air, carbon monoxide and hydrogen as well as many other gases in smaller quantities. The effect of the plasma now depends critically on the plasma temperature. Not all of the feed gases go through the hottest parts of the plasma. The plasma is simulated with three streams. The cool stream is the gases that move close to the wall and skirt around the plasma. These are kept below 900 °C to ensure a long life for the plasma vessel. Some small part of the plasma will be very hot and is taken here to have a temperature of 4000 °C. This temperature is sufficient to see the synthesis of many of the high-temperature species shown in Figure 2 that might be persistent in the output streams. The remainder of the gaseous input feed is assumed to be heated to the average output temperature from the plasma chamber. The flow diagram in Figure 5 shows the streams being remixed after the plasma chamber and before the gasification chamber. This mixing step exchanges heat while maintaining the molecular constitution so that all the plasma exhaust is at the same temperature. After mixing, the stream is split so that a fraction of the Syngas is extracted, then cooled.

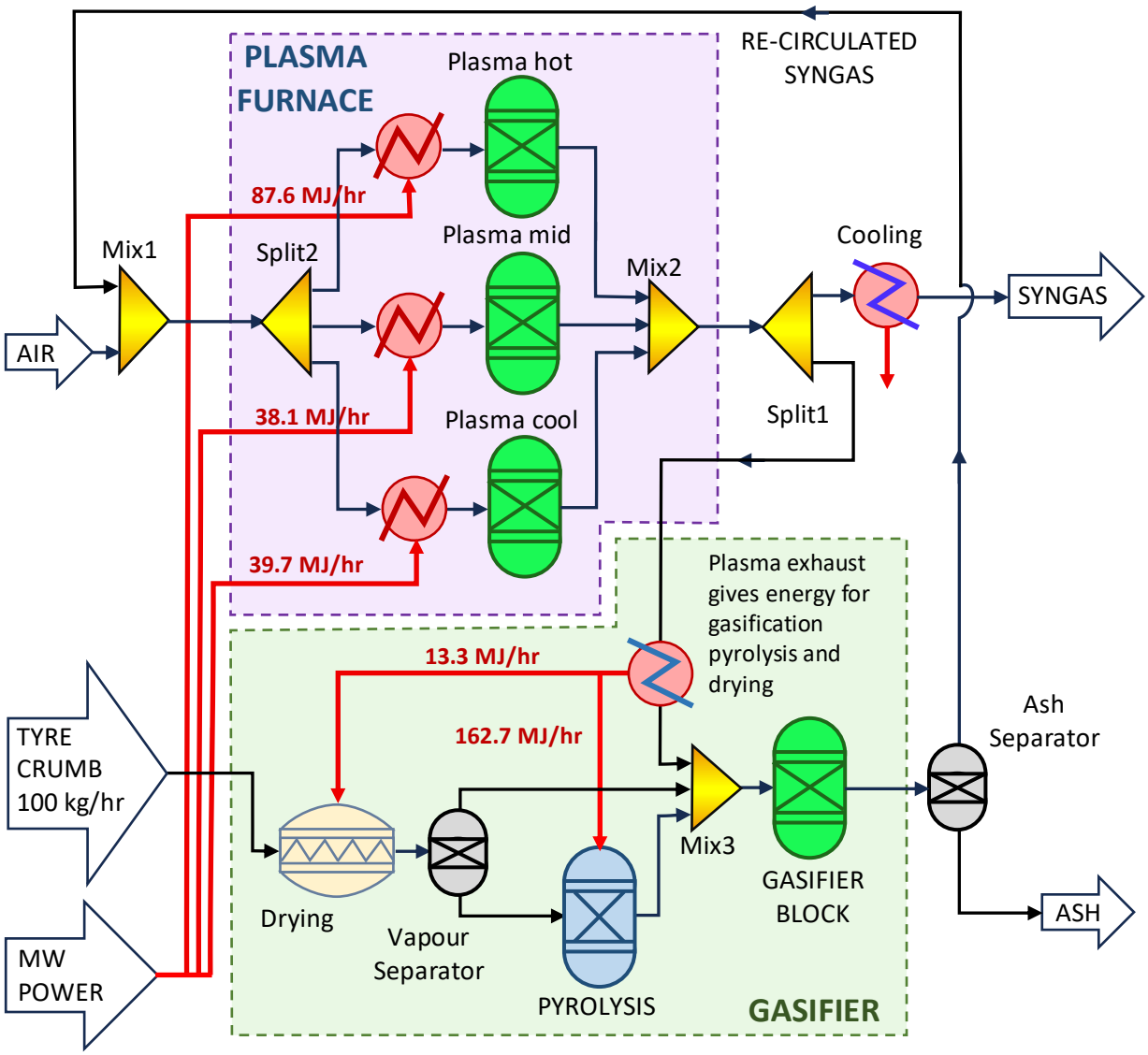


Figure 5 *Process flow diagram used for ASPEN Plus simulation with recirculation*

Selected results for the output composition are presented in Figure 6. The result shown was generated with a feedstock input of 100 kg/hr and no recirculation (namely, Case 1).

The ASPEN Plus calculation did not include all high-temperature species as outputs, because only temperatures appropriate to the gasification chamber were considered. Two higher hydrocarbons were included as output species, but their concentrations were below 1 ppm; hence do not show due to the scale used. As can be seen, there is an optimum airflow of 16.5 kmol/hr that removes all the fixed carbon. If excess air is used, then the carbon dioxide content increases, which is undesirable. A very small excess airflow has the benefit of reducing HCN production. At airflows of 16.0, 16.5 and 17.0 kmol/hr, the mole fraction of HCN is 3.2e-3, 4.3e-5 and 4.0e-6, respectively; hence, this step gives orders of magnitude reduction in production. At an airflow of 16.5 kmol/hr, the exhaust gas leaves at 1784 °C.

This heating is excessive and would be difficult to recover, hence one would probably want to mix in some steam and increase hydrogen production. It will be seen that it is also possible to reduce this temperature with recirculation, which reduces the microwave input.

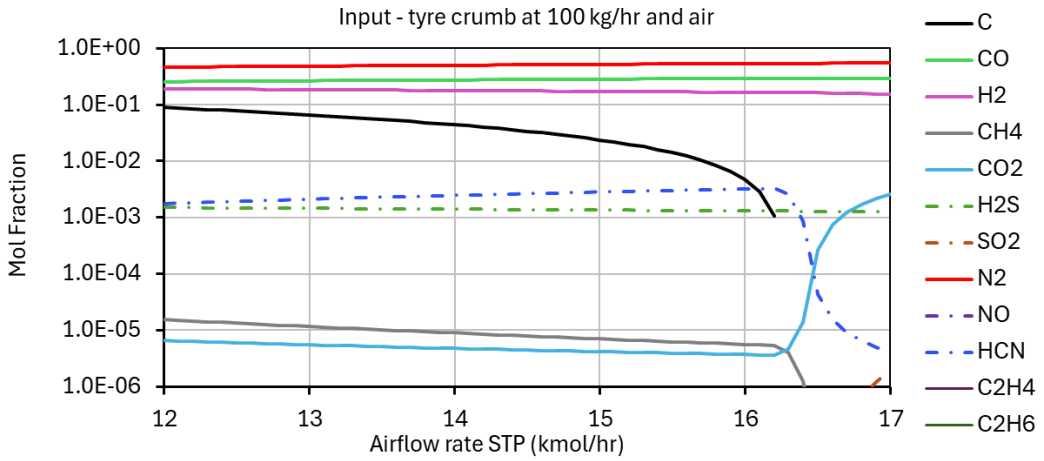


Figure 6 *Chemical equilibrium of tyre crumb plus air at constant Enthalpy and Pressure as a function of airflow as determined by ASPEN Plus (no recirculation)*

The ASPEN Plus calculation includes the sulphur content of the tyre crumb, and Figure 6 shows that if there is no oxygen available, then the sulphur forms H_2S. If there is surplus oxygen, then the sulphur will form SO_2. This is important with respect to the desulphurization of the syngas [19].

In the previous section, it was noted that a feature of the Lancaster University test rig would be the ability to recirculate hot gases. Not only does this allow better control of the plasma, but it also enhances efficiency as the microwave power input is reduced; consequently, less heat has to be recovered from the output stream. Figure 7 shows output composition for processing with 80% recirculation of the exit stream from the gasification RGibbs block (Case 2). The difference now is that for Case 1, the microwaves provide all the heating, whereas for Case 2, recirculated gases provide much of the heating. For Case 2, the temperature of hot gases to the gasification RGibbs block varies in the range of 1140 ºC-1220 ºC.

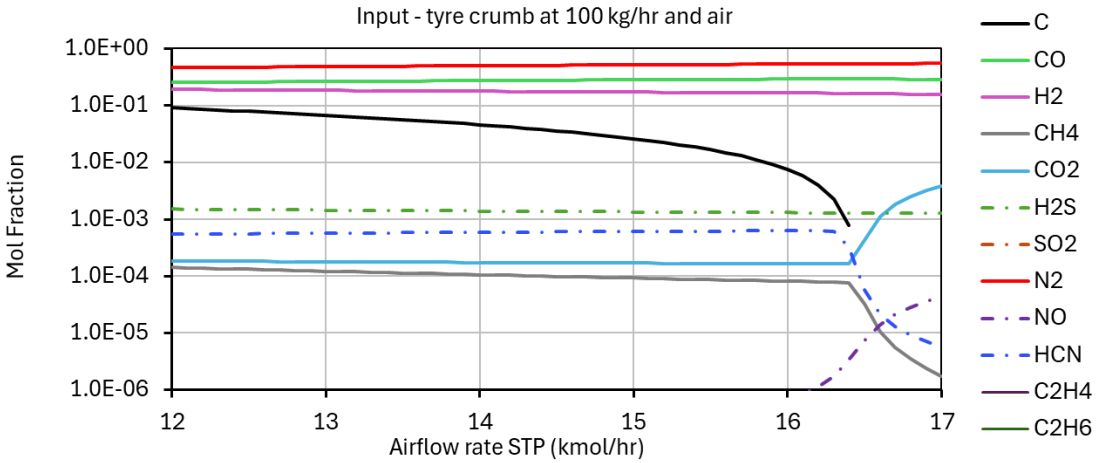


Figure 7 *Chemical equilibrium of tyre crumb plus air at constant enthalpy and pressure as a function of airflow with 80% recirculation as determined by ASPEN Plus*

Figure 8 compares the exhaust temperatures for Case 1 (no recirculation) and Case 2. The reaction to produce carbon monoxide is slightly exothermic; hence, the exhaust gases are hotter than the input stream temperature. With 80% recirculation, there is nominally four times less heating of the exit stream as the heat of reaction is being transferred back to the input stream. The ASPEN Plus calculation gives a factor of 2.8 for the reduction in microwave power required with recirculation for the optimal flow rate of 16.5 kmol/hr. The reaction to produce carbon dioxide is strongly exothermic; hence, for flow rates above the optimal, the rate of heating with airflow increases significantly.

Comparing compositions for Case 1 and Case 2, given in Figures 6 and 7, respectively, the differences for hydrogen and carbon monoxide production are negligible, as would be expected. There are small

differences in carbon dioxide and hydrogen cyanide production. The final syngas calorific value is nominally the same, with and without recirculation; however, recirculation significantly reduces the cost of production.

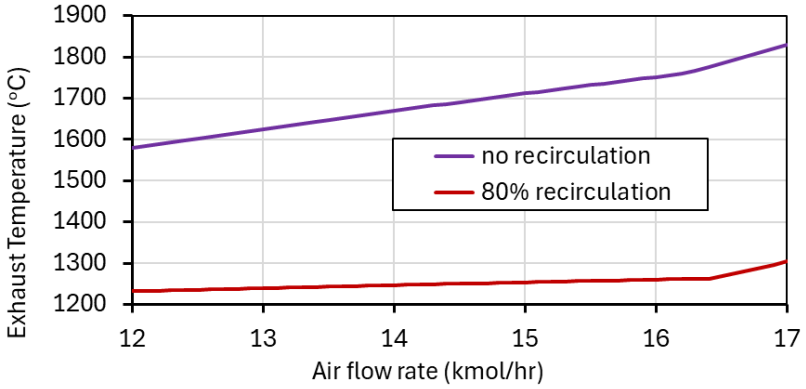


Figure 8 *Exhaust temperatures compared for the case with and without recirculation*

Conclusions and future plans

A stable atmospheric-pressure microwave-induced plasma has been successfully generated within a steel vessel, demonstrating a controllable and repeatable process. The resulting high-temperature exhaust has been shown to possess the necessary thermal and reactive characteristics to enable the gasification of various waste feedstocks, including tyre crumb. This study has established the key operational parameters for efficient plasma generation and provided foundational data for assessing tyre-derived materials as viable inputs for plasma-assisted gasification systems.

The findings highlight the potential of microwave-induced plasma technology as a cleaner and more efficient alternative to conventional thermal processes, offering enhanced destruction of organic compounds and reduced harmful emissions. By achieving stable plasma operation at atmospheric pressure, the study advances the feasibility of compact, modular waste-to-energy systems that could be deployed closer to the source of waste generation, reducing transportation costs and environmental impact.

The next phase of this research will involve practical gasification trials using tyre crumb as the primary feedstock, conducted both with and without exhaust gas recirculation (EGR). These experiments will systematically evaluate system performance under varying operational conditions to determine optimal configurations for energy efficiency, syngas quality, and emission control. Furthermore, future work will extend to process modelling, energy balance analysis, and scalability assessment, with a focus on integrating the plasma gasification unit into broader circular economy frameworks. The outcomes are expected to provide critical insights into the viability of microwave-induced plasma gasification as a sustainable pathway for converting problematic waste streams, such as end-of-life tyres, into valuable energy and chemical products.

References

1. Nations, U., *The Sustainable Development Goals Report.* 2024.
2. Statista, *Projected worldwide tire market volume from 2014 to 2018 (in billion units)*. 2016.
3. Okonkwo, F.O., et al., *Health Implications of Occupational Exposure of Butchers to Emissions from Burning Tyres.* Ann Glob Health, 2018. **84**(3): p. 387-396.
4. Levendis, Y.A., et al., *Comparative Study on the Combustion and Emissions of Waste Tyre Crumb and Pulverized Coal.* Environmental Science & Technology, 1996. **30**(9): p. 2742-2754.
5. Machin, E.B., D.T. Pedroso, and J.A. de Carvalho, *Energetic valorization of waste tyres.* Renewable and Sustainable Energy Reviews, 2017. **68**: p. 306-315.

6. Janajreh, I., S.S. Raza, and A.S. Valmundsson, *Plasma gasification process: Modeling, simulation and comparison with conventional air gasification.* Energy Conversion and Management, 2013. **65**: p. 801-809.
7. Breeze, P., *Gas-Turbine Power Generation*. 2016, Chantilly, UNITED KINGDOM: Elsevier Science & Technology.
8. *The highway code - Annex 6. Vehicle maintenance, safety and security.*, D.f. Transport, Editor. 2025, Driver and Vehicle Standards Agency (DVSA).
9. Sienkiewicz, M., et al., *Progress in used tyres management in the European Union: A review.* Waste Management, 2012. **32**(10): p. 1742-1751.
10. Oboirien, B.O. and B.C. North, *A review of waste tyre gasification.* Journal of Environmental Chemical Engineering, 2017. **5**(5): p. 5169-5178.
11. Machin, E.B., D.T. Pedroso, and J.A. de Carvalho, *Technical assessment of discarded tires gasification as alternative technology for electricity generation.* Waste Management, 2017. **68**: p. 412-420.
12. Cunliffe, A.M. and P.T. Williams, *Composition of oils derived from the batch pyrolysis of tyres.* Journal of Analytical and Applied Pyrolysis, 1998. **44**(2): p. 131-152.
13. Agency, E.-E.C. *Granules and mulches on sports pitches and playgrounds*. [cited 2025 September 19]; Available from: https://echa.europa.eu/hot-topics/granules-mulches-on-pitches-playgrounds.
14. Vecten, S., et al., *Experimental study of steam and carbon dioxide microwave plasma for advanced thermal treatment application.* Energy, 2020. **207**: p. 118086.
15. Vecten, S., et al., *Experimental investigation of the temperature distribution in a microwave-induced plasma reactor.* Fuel Processing Technology, 2021. **212**: p. 106631.
16. Pack, B.W. and G.M. Hieftje, *An improved microwave plasma torch for atomic spectrometry.* Spectrochimica Acta Part B: Atomic Spectroscopy, 1997. **52**(14): p. 2163-2168.
17. Wynn, A.P., et al. *Development of a 300 kW CW L-band industrial heating magnetron*. in *Fifth IEEE International Vacuum Electronics Conference (IEEE Cat. No.04EX786)*. 2004.
18. Diallo, A.D.D., et al., *Simulation of biomass and municipal solid waste pellet gasification using Aspen Plus.* IOP Conference Series: Materials Science and Engineering, 2021. **1192**(1): p. 012023.
19. Okoro, O.V. and Z. Sun, *Desulphurisation of Biogas: A Systematic Qualitative and Economic-Based Quantitative Review of Alternative Strategies.* ChemEngineering, 2019. **3**(3): p. 76.