Abstract: Despite its long history of technological development, much charcoal production still relies on polluting and inefficient technologies utilizing traditional kiln designs. In addition to the need for improved charcoal production systems, the growing interest globally in pyrolysis of biomass to generate biochar as a soil fertility improver and for climate change mitigation may drive an increasing demand for such technologies. Accordingly, there is a clear need in developing countries for access to safe, affordable, and efficient open-source designs and technology that can be fabricated locally. The design described here includes computational fluid dynamics modeling which demonstrated that the design exhibits a stable flow and combustion pattern. A hazard and operability (HAZOP) study, mass and energy modeling, and costing of all components and fabrication were also conducted for a prototype kiln that will accept up to 250 kg biomass h\(^{-1}\). Fabrication and installation costs were estimated using actual commercial quotations based on detailed engineering drawings and design, and were found to be $580 000 for a 250 kg h\(^{-1}\) unit. We therefore find that this pyrolysis system promises to be economical on a small scale. It can utilize waste lignocellulosic materials for feedstock, thus alleviating demand pressure on woodlands to provide feedstocks. It was, therefore, concluded that the pyrolysis unit described here promises to provide an affordable and efficient open-source design that can be fabricated locally in developing countries without licensing restrictions or royalties. © 2017 The Authors Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd

Supporting information may be found in the online version of this article.

Keywords: pyrolysis; charcoal; biochar; open-source technology
**Introduction**

Pyrolysis of biomass to create charcoal is one of the oldest known technologies.\(^1\) Despite its long history, biomass pyrolysis technology remains under active development today. Globally, much charcoal production still relies on highly polluting and inefficient technologies utilizing traditional kiln designs.\(^2\)\(^-\)\(^4\) There has, therefore, been much interest recently around the need to increase adoption of improved (safe, affordable, and efficient) pyrolysis kilns.

Pyrolysis of biomass yields both a carbon-rich solid product (known as charcoal when intended and appropriate as a fuel, or biochar when used as a soil amendment). It yields volatile and gaseous products that can be combusted directly as fuel, or upgraded to higher value biofuels. Thermodynamics indicates that, provided the biomass water content is not too high, the enthalpy in the pyrolysis gases and volatiles (PGVs) exceeds that required to dry, heat, and pyrolyze the feedstock.\(^5\)\(^-\)\(^7\)

In addition to the need for thermally integrated efficient pyrolysis equipment that, ideally, is a net producer rather than consumer of biofuels, there is also a clear need in developing countries for access to safe, affordable, and efficient open-source designs and technology that can be fabricated locally without licensing restrictions or royalties.\(^3\) This paper describes such a design, including computational fluid dynamics (CFD) modeling, a hazard and operability (HAZOP) study, mass and energy modeling, and costing of all components and fabrication for a prototype kiln that will accept up to 250 kg h\(^{-1}\). As demonstrated in the fabrication costings, this pyrolysis system promises to be economical on a small scale. It can utilize waste lignocellulosic materials for feedstock, thus alleviating demand pressure on woodlands to provide feedstocks. In addition, any excess combustion enthalpy in the PGVs from suitable feedstocks can provide heat or be used to generate electricity or liquid fuels.\(^6\)\(^,\)\(^8\)

Comprehensive engineering drawings, and design and fabrication details are available in the online supplementary information.

**Design criteria and objectives**

The pyrolysis retort was designed to process biomass with a moisture content up to 30% at temperatures ranging from 450°C up to 600°C (with operation at the higher temperature limited to a maximum of 1 h). The reactor comprises three main sections for: (i) drying, (ii) torrefaction and pyrolysis, and (iii) combustion of the PGVs. Incoming biomass is pre-heated by exhaust gases from the reactor as it is delivered by conveyor into a feed hopper, whence it is fed into the reactor by a screw auger. The feed system was designed to accommodate woodchips with a maximum dimension of 10 mm. If this design is to be adapted to other feedstocks, then a corresponding alteration to the feed system may be required, because use of an incompatible feedstock is a common cause of operating problems and failure of the feed system. Hot exhaust from the combustion chamber flows through the annulus of the double-walled auger screw, both to provide further initial drying and pre-heating of the biomass, and to prevent ingress of air into the reactor by creating a slight negative pressure which draws any entrained air together with the flue gases and steam from the drying out through the flue. Most of the drying then occurs within the first section of the reactor, where moisture is driven upward, exiting through the hood outlet (Fig. 1).

**Figure 1. Simplified schematic of reactor design.**
impelled through the trough at the bottom of the pyrolysis reactor by the screw auger. Process heat is delivered to the biomass by conductive heat transfer through the trough walls from the combustion chamber located beneath the pyrolysis and drying chambers. A small amount of recirculated flue gas also enters at the beginning of the pyrolysis section to ensure that the gas space above the pyrolyzing biomass is maintained at 450—500°C, to prevent tar condensation. Changing the flow of recirculated flue gas in this pyrolysis section also controls the final temperature at which the biochar is generated. More recirculated gas results in high chamber temperatures and higher temperatures the biochar is exposed to. Three spray nozzles are provided in the pyrolysis chamber for steam production and to lower the oxygen concentration from entrained air.

The biochar terminates at a rotary self-sealing valve, which discharges by direct drop into a 55-gallon (200 L) drum. The biochar can be activated with steam provided by demisting nozzles at the biochar outlet.

The PGVs produced in the pyrolysis chamber pass through an external duct to a gas/air mixer. This mixer acts as an input to a thermal oxidizer. If required, some of the producer gas can also be directed to another external process (such as biofuel production) before mixing with air, via a valve-controlled manifold. The mixer consists of three sections: (i) an outer chamber where air is introduced and passes through six swirl vanes, (ii) an air ejector, and (iii) dual pilot burners in the middle of the thermal oxidizer chamber. The two pilot burners are fueled by liquefied petroleum gas (LPG). The use of two LPG burners provides improved control of the heating zones, while allowing one burner to be turned off to conserve fuel. One burner must always remain on, at low power, as a pilot light to reignite any flame outs. The temperature in the combustion chamber can be regulated by the amount of air injected into the burner, and by varying the two LPG burners. It was initially proposed to preheat combustion air by passing it through a pipe within the combustion chamber. However, air preheating was eliminated during the design process because thermal cycling of the hot pipe would cause premature failure, and because commercial burners are designed to accept air at no higher than 150°C, above which temperature thermal NOx emissions become excessive and gas velocities can exceed flame speed causing unstable burner operation. The bulk of combustion products exit via two outlets at the far end of the combustion chamber from the burner. The flue gases are then used for preheating of biomass and combustion air. Adjustable bleed flaps at the downstream end of the combustion chamber divert a portion of the hot combustion gases around the trough walls (Supporting Information Fig. S2). Through a set of bleed vents in the trough some of the hot gases enter the drying chamber. This bleed enhances the moisture removal, and drives recirculation of PGVs through the reactor.

Comparison to other pyrolysis reactor designs

Charcoal and biochar can be produced using a range of different technologies at the household, medium, or large industrial scale. Given that charcoal-making is an ancient industry, a large number of reactor designs have evolved over time. Some of the main technologies are described herein, with more detailed descriptions of the different designs and technologies available in references 9–13.

The most primitive forms of pyrolysis reactor are the pit kiln and the mound kiln, in which air is partially excluded from a smoldering pile of wood by covering it with earth. These kilns are labor intensive, with constant attention required to open and shut air access to maintain just sufficient combustion to heat the process, without burning too much of the charcoal. Traditional earth kilns remain in widespread use today, despite having high labor costs, low yields, variable and heterogeneous charcoal quality, and producing large amounts of pollutants (methane, volatile organic compounds, and soot), which are not fully combusted before venting.2 Batch kilns that operate according to similar principles, but are constructed of brick or metal offer some improvement in yields and emissions, but still have low performance in these regards compared to modern industrial pyrolysis reactors. Because of the ongoing widespread use charcoal kilns, which are inefficient, polluting, and unable to utilize more sustainable biomass resources such as crop residues, improving the sustainability of charcoal production has been recommended as a key priority and the most effective and immediately realizable means to enhance the sustainability of household cooking fuel in developing countries.14–17

An improvement in emissions from batch kilns can be achieved by ensuring complete combustion of PGVs prior to venting. If the heat from combustion of PGVs is also used to increase thermal efficiency by providing process heat to the pyrolysis zone, then such reactors are often referred to as retorts, rather than kilns. Examples of pyrolysis retorts that designed to be appropriate for developing countries include the Adam retort (constructed from bricks or clay blocks) and drum reactors (often based around discarded 55-gallon oil drums) in which material to be carbonized is placed within the drum, and a fire is maintained...
beneath it to provide process heat. In some, but not all drum reactor designs, the PGVs are channeled into the fire zone beneath the drum where they combust and contribute towards the process heat. There has also been some recent interest in ‘flame carbonizers’ as a simple, low-cost means to produce charcoal, in which wood is simply stacked in an open topped vessel which burns from the top, thus maintaining a low oxygen, heated pyrolysis zone below the flame. However, flame carbonizers are labor intensive, and have a low thermal efficiency as much of the heat rises from the flames to be lost to the atmosphere.

The batch process designs described above all suffer from poor heat transfer, i) through the mass of material in the batch (particularly in externally heated processes), and ii) into the biomass particles themselves, which can be a rate limiting process, particularly when large pieces of wood are carbonized to create lump charcoal. The lengthy reaction time required for production of lump charcoal in batch kilns and retorts contributes to low efficiency, because considerable heat is lost to the environment over the course of the carbonization process, which can take many hours or even several days.

A large improvement in reaction times (down to less than an hour), and thus also thermal efficiency, can be achieved if the biomass is finely divided to improve heat transfer into the interior of the biomass particles. The resultant particulate char is well suited to use as biochar, but may require further briquetting if it is to provide a drop-in replacement for lump charcoal. Heat transfer into the bulk material can be improved either by using an internal heat carrier that intimately mixes with the feedstock, or by continuous mixing of the feedstock to ensure that it all comes into close thermal contact with an external heating surface. Many production-based continuous pyrolysis reactors are rotary kiln types that use indirect heating as the means of heat transfer. Internal heat carriers include heated recirculating pyrolysis gases in a fluidized bed (a system most often proposed for fast pyrolysis for bio-oil production), a heated particulate solid such as sand (as, for example, in the Lurgi reactor), or even a liquid such as molten salts. Designs that use an internal heat carrier are typically better suited to industrial applications in a more developed setting, due to the greater complexity, higher capital cost, and greater electricity demand for external prime movers.

Externally heated stirred reactors are well suited to also being continuous rather than batch processes, because a single prime mover (often a screw drive) can perform the dual functions of moving material through the reactor while also mixing it to ensure uniform heating of all the biomass. This is the class of reactor of the design described here. Many examples of continuous externally heated reactors use a screw-drive located within a cylinder. However, in such designs most heat transfer into the feedstock occurs only on the lower parts of the tube where the feedstock is in contact (due to gravity). The current design, therefore, places the screw drive within a simple sheet metal trough that is heated only from below, thus reducing fabrication and material costs without compromising efficiency. The use of a sheet metal trough design also facilitates the introduction into the design described here of controllable bleed flaps and recirculation vents that provide greater control over process conditions than can be achieved in most comparable technologies.

More advanced continuous retorts, which are better suited to larger scale industrial applications include the Lambiotte retort, the Lurgi reactor, and continuous multiple hearth reactors. Ultimately, the best choice of reactor type will vary depending on the intended scale, location, feedstock, and socio-economic environment. However, the continuing widespread use of inefficient and polluting traditional kilns, together with the active development of improved low-cost solutions that is under way indicate that there is a clear need for an intermediate technology that provides the advantages of higher efficiency, higher yield, and lower operating costs offered by advanced industrial continuous retorts, while also being suited to low cost and small scale rural operations in developing countries.

Hazard and operability study

A hazard and operability study (HAZOPS) is a structured and systematic examination of a process to identify and evaluate risks to personnel or equipment. As part of the design process, a HAZOPS was conducted by an independent engineering firm (O’Brien & Gere) utilizing a commercial software package for conducting Process Hazard Analysis (PHAWorks from PrimaTech), with the results of the study being used to modify the design and the recommended standard operating procedures (SOP).

No hazards were found to have a risk rating lower (more severe) than three. The nine hazards with a risk rating of three are shown in Table 1, together with the recommended modifications to the design and SOP to mitigate these risks.

Computational fluid dynamics

Computational fluid dynamics (CFD) modelling was conducted using ANSYS Fluent software to assess the thermal-fluid and combustion performance of the reactor. The reactor was represented as a high-resolution grid (approximately 300 000 polyhedral cells) to resolve the smallest geometrical dimensions and regions of sharp curvatures.
Table 1. Results of hazard and operability study, showing the most severe risks identified. A complete table showing all hazards is given in the Supporting Information. S = Severity (1–5), L = Likelihood (1–5), R = Risk (1–10), where 1 is high; SOP = standard operating procedure; VFD = variable frequency drive; FCV = flow control valve; LSL = low level sensor; MOC = material of construction; BRT = cooling water break tank.

| Generator Set | WHAT IF... | HAZARD | CONSEQUENCES | SAFEGUARDS | S | L | R | RECOMMENDATIONS |
|---------------|------------|--------|--------------|-------------|---|---|---|-----------------|
| The GenSet runs out of fuel and all power to the system is OFF | Hot combustion gases present in the combustion chamber | Potential fire in feedstock conveyor which poses a risk to personnel and equipment | Make motorized FCV on combustion chamber AND genset, fail-closed to force hot gases through stack | 1 | 3 | 3 | Operator to check fuel per SOP. |
| | Potential for fire/explosion in the pyrolysis screw conveyor due to stopping the screw with hot materials present. | Personnel or equipment damage. | Fail-open water sprays over length of pyrolysis screw trough. In addition, the two combustion gas diverter valves shall be fail-closed so no additional combustion chamber gases enter the pyrolysis screw housing. | 1 | 3 | 3 |

| Solid Feed System | WHAT IF... | HAZARD | CONSEQUENCES | SAFEGUARDS | S | L | R | RECOMMENDATIONS |
|------------------|------------|--------|--------------|-------------|---|---|---|-----------------|
| Jam in screw operation | Fire | Material in screw will continue to be heating by system off-gas. Potential for ignition of biomass. | Screen on feed hopper inlet. Tramp metal separator. High amperage alarm. Add auxiliary contact for screw VFD as a system interlock and close combustion chamber FCV to restrict hot gas flow to screw. | 1 | 3 | 3 | SOP to address a controlled shutdown under this event. |
| Discharge rotary valve jams | Fire | Material in screw will continue to be heated by system off-gas. Potential for ignition of biomass. | Add auxiliary contact for rotary valve VFD as a system interlock and close combustion chamber FCV to restrict hot gas flow to screw. | 1 | 3 | 3 | SOP to address a controlled shutdown under this event. |
| Backflow through feed hopper | Exposure to personnel to hot gases and expulsion of feedstock materials | Personal injury. | LSL to alarm the operator of a low hopper level. LSL will interlock system operations. | 1 | 3 | 3 | SOP to address a controlled shutdown under this event. |
| WHAT IF... | HAZARD | CONSEQUENCES | SAFEGUARDS | S | L | R | RECOMMENDATIONS |
|------------|--------|--------------|------------|---|---|---|----------------|
| The screw motor fails | Unable to move feedstock through kiln | Fire, explosion | Drive failure alarm and high amperage alarm as interlocks. This would engage an emergency shutdown. | 1 | 3 | 3 | Add an emergency water supply as a redundant back up since the supply of water is critical to safety. Address maintenance in SOP. |

**Pressure Relief Valves**

| WHAT IF... | HAZARD | CONSEQUENCES | SAFEGUARDS | S | L | R | RECOMMENDATIONS |
|------------|--------|--------------|------------|---|---|---|----------------|
| There is a high gas pressure event of syngas from the pyrolysis kiln | High gas pressure | Equipment failure, personnel exposure | Add a 3-way valve to ensure an open path for ventilation. | 1 | 3 | 3 | Recommend re-evaluating MOC of existing tank away from plastic. Operator training and SOP. |

**Water Supply**

| WHAT IF... | HAZARD | CONSEQUENCES | SAFEGUARDS | S | L | R | RECOMMENDATIONS |
|------------|--------|--------------|------------|---|---|---|----------------|
| Low water in BRT-01 | Little or no cooling water for pyrolysis temperature control Restricted flow in outlet water lines | Fire or explosion Fire of explosion | LSSL is an operational interlock. Strainer on tank Outlet. | 1 | 3 | 3 | Operator training per SOP. Add an emergency water supply as a redundant back up since the supply of water is critical to safety. Maintenance training per SOP. |
in the reactor, while ensuring a smooth growth of the size of the cells to prevent computational overload.

The SST $\kappa$-$\omega$ turbulence model is used in the calculations. It offers the best predictions accuracy and numerical stability among the various two-equation turbulence models, especially for flows with regions of flow separation and recirculation. Radiative exchange was modeled using the Discrete-Ordinate (DO) thermal radiation model (the most sophisticated model available in commercial CFD packages). This model accounts for radiation exchange between surfaces, and thermal radiation from reacting gases, and solid particles. The DO model is computationally intensive; therefore, it was activated once the solution was partially converged. For the process chemistry, both homogeneous and heterogeneous reactions were included in the calculations. Volatiles released during pyrolysis are highly variable, and contain a wide range of compounds ranging from small to heavy hydrocarbon chains; for example, CH$_4$ to C$_6$H$_{10}$O$_5$ (tars). The focus in the present study was to evaluate the heat release from the combustion of volatiles, rather than the species breakdown. Therefore, the volatiles were treated as a single compound with a generic formula, C$_{w}$H$_{x}$O$_{y}$N$_{z}$, with w, x, y, and z quantified by the ultimate volatiles, rather than the species breakdown. Therefore, the study was to evaluate the heat release from the combustion of volatiles, rather than the species breakdown. Therefore, the volatiles were treated as a single compound with a generic formula, C$_{1.12}$H$_{2.09}$O$_{0.89}$N$_{0.0074}$ as a representative formula for the volatiles. The chemistry of the gaseous and solid phase reactions was represented using the multistep chemical mechanism listed in Table S3. A propane reaction in the chemistry model (Table S3) accounts for the pilot flame in the combustion chamber, which was assumed to be operating constantly at 5kW. Turbulence-Chemistry Interactions were modelled using the Finite-Rate/Eddy Dissipation (FRED) concept. The FRED model computes the rate of reaction (using the chemistry in Table S3) for each species based on both the Arrhenius rate and the turbulent mixing rate and uses the smaller of the two.

The walls of the reactor were assumed to be thin surfaces. The conjugate heat transfer to and from the walls was computed using a built-in one-dimensional model that accounts for wall thickness, and the physical and thermal properties of the walls. It also accounts for radiative heat transfer. The external walls of the reactors were assumed to be insulated with 50 mm of Calcium Silicate board, followed by a 100 mm of Kaowool.

The trajectory and properties (composition, temperature, etc.) of the woodchip particles and their interaction with the gaseous phase was modeled with a Lagrangian-Eulerian Discrete Particle Model (DPM). The DPM approach is valid for multiphase flows with low particulate volume fraction in the gas-solid mixture (< 0.1), which is the case in the present reactor. The woodchips were modelled as solid particles that experience inert heating, vaporizing, and boiling of moisture content, followed by further inert heating, devolatization, and (subject to temperature and oxygen conditions) surface reactions. These processes are controlled by the local coupling between solid and gas phases, which is determined by the rates of heat and mass exchanges between the phases. The biomass particles are introduced in the trough with velocity components to emulate the effect of the rotating auger. To account for the effect of the non-spherical shape of the biomass on the drag coefficient of the particles (hence its trajectory and properties), a shape factor is introduced. Assuming a 10-mm cubic woodchip particle with an elongation of 10% in one direction, a shape factor of 0.805 is used in the model. Woodchips tend to swell as the moisture content increases, and shrink as the moisture content reduces. Considering that the woodchip particles in the reactor undergo an enhanced drying process, it is reasonable to assume that the particles will most likely experience mainly shrinkage. Accordingly, a ‘Swelling’ coefficient of 0.94 was used. To account for the effect of the gaseous turbulent velocity fluctuations on the particle trajectories, a stochastic tracking model (using the Discrete Random Walk model) was used with ten injection tries per particles per location.

CFD was performed on two model configurations: W+, in which water spray (50 kg/h) injectors are installed in the drying chamber, and W-, a reference configuration without water spray injectors.

The main impact of injecting water was, as expected, on the temperature field, with the mean temperature in the drying chamber being reduced from 1220 °C, to a manageable 820 °C (Fig. 2). The mean temperature in the pyrolysis chamber is also reduced by 214 °C, to 631 °C. The mean temperature in the combustor is, however, only reduced by 124 °C, to 1037 °C, by the water injection. W+ also had a positive effect on the velocity field by improving the symmetry of the counter-rotating vortices, and eliminating the vortex in the drying chamber (Figs 2(c) and 2(d)). A slight asymmetry persists in the flow properties at the outlets of the combustor, due to the swirl effect of the combustion air that persists along the entire length of the combustion, and because of the change in the geometry from opening of the bleed flaps.

In both W+ and W- configurations, the solid-phase particles remain confined to the trough with no evidence of particles carryover into the top chamber or to the combustion chamber. This model assumes a uniform (10 mm) particle size. The dynamics of smaller particles may be different and some carryover might occur. Investigating and quantifying this scenario is beyond the scope of the present work but should be considered in future studies. In addition to particle size, the CFD results will also depend on differences in...
feedstock water, lignin, & ash content, and particle shape. Conducting CFD analysis on the full range of potential feedstocks for which this reactor may be applicable is beyond the scope of this study, but should be considered by anyone intending to adapt the design to a different feedstock.

Fabrication and installation costs

Fabrication costs (in 2014 USD) were estimated by obtaining quotes from manufacturers and suppliers for all components and materials required in the fabrication of the kiln (Table 2). The total cost was estimated at $580,000, of which the largest components were $360,000 for fabrication (including labor, materials, and equipment), a $50,000 contingency allowance, and $40,000 for the control system (parts, labor, and installation).

Conclusions

The proposed design was found to exhibit a stable flow and combustion pattern by the CFD analysis, provided the bleed vents are kept fully or partially opened during a steady operation of the reactor. Injection of 50 kg/h water droplets into the drying chamber was found to be effective at reducing the mean temperature of the chambers by 400°C, 214°C, and 124°C in the drying, pyrolysis, and combustion chambers, respectively. Particle tracking showed no carryover of particles outside the trough into any of the chambers.
Table 2. Fabrication and installation costs for pyrolysis kiln in 2014 USD.

| Item                                      | Cost (USD) |
|-------------------------------------------|------------|
| Fabrication Labor and all supplied equipment | 356,432    |
| Contingency                               | 50,000     |
| Control System integration, labor for GUI, software, industrial laptop | 40,000     |
| Hot Commissioning and startup             | 35,000     |
| Design/Install Panel Cabinet w/ 4 VFD, eng, cadd, build & test | 34,000     |
| Feedstock Conveyor System variable speed with drying capability | 31,000     |
| Design/Install Plumbing & Wiring of kiln   | 21,000     |
| Instrumentation software and data acquisition hardware | 11,000     |
| Packaging in shipping container           | 5,500      |
| **Total**                                 | **583,932**|

The main operational hazards identified were associated with (i) loss of electrical power from the generator running out of fuel, (ii) blockages or backflow in the biomass feed system or, (iii) failure of the screw auger that transports material through the kiln, (iv) high gas pressure event within the kiln, or (v) running out of cooling water. The risk of these hazards can be addressed and mitigated through appropriate measures being taken in the standard operating procedures and by the addition of a back-up water cistern.

The overall fabrication and installation cost of $580,000 for a 250 kg h⁻¹ unit, assuming a capacity factor of 0.75 equates to $355 (Mg feedstock yr⁻¹)⁻¹, which is in the same range as previously published assumptions. We conclude, therefore, that the pyrolysis unit described here promises to provide an affordable and efficient open-source design that can be fabricated locally in developing countries without licensing restrictions or royalties.

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