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SHORT COMMUNICATION

Process Design and Operation of a Wood Charcoal Retort

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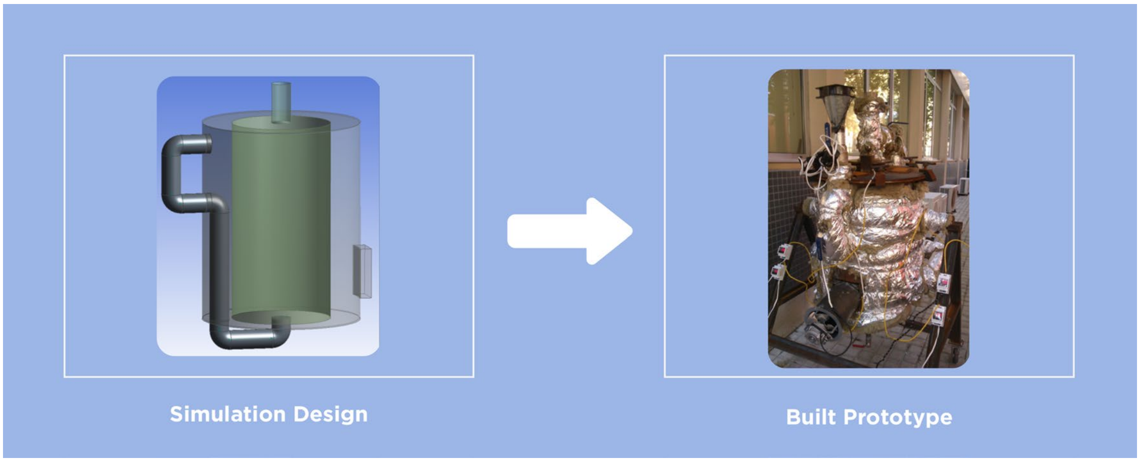
Abstract An efficient approach for the development of a compact integrated wood charcoal retort was designed. The key fundamental requirements to guarantee efficiency and productivity are initially investigated via CFD simulations to identify the temperature and velocity profiles inside the unit. The final compact design is comprised of a double vessel arrangement where the wood to be carbonized is placed in the central vessel (i.e. carbonizer). A flue-gas recycle line leaves the outer vessel (i.e. combustion furnace) to preheat the wood in the carbonizer during startup. This design allows the syngas/methane leaving the carbonizer to be re-circulated into the combustion furnace to provide the necessary energy. The integrated compact retort system is further tested experimentally; only 2–3 h were needed to achieve complete carbonization of oak wood. Various temperatures are achieved during operation, the maximum of which is at 900 °C. The charcoal yield ranged between 37 and 46% on a dry basis, and the charcoal carbon contents were between 73 and 87%.

Graphical Abstract



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Keywords Biomass conversion · Process design · Charcoal production · Computational fluid dynamics · Process optimization

Introduction

Charcoal has become an important energy source in most developing countries as it provides cleaner combustion and a higher calorific value than wood: dry charcoal has a high gross calorific value (GCV) of 33 MJ/kg [1], whereas the direct burning of wood or biomass gives only about 10% of useful energy [2]. Transforming wood into charcoal is an ancient tradition that has domestically provided fuel for heating and cooking. With the recent trend in alternative energy, and the rise in awareness of depleting liquid fuel resources and their negative effects on the environment, producing charcoal from wood has strongly returned to the spotlight providing specialists with a challenging process to optimize. In fact, worldwide wood charcoal production is steadily on the rise with production rates more than doubling since the 1980s, exceeding 53 Mtons in 2014 [3] as shown in Fig. 1. This is equivalent to a minimum energy output of 55 gigawatts per year. Brazil continues to be ranked number one at 7.24 Mtons or ~7.6 gigawatts per year, followed by Nigeria and Ethiopia at 2 Mtons each (i.e. 4.4 gigawatts per year) [3]. However, the inherent inefficiencies in charcoal production are causing a heavy strain on local forests and the environment as a whole: the theoretical yield of charcoal from biomass lies in the range of 50–80% on a dry weight basis. The traditional methods adopted for charcoal production are mostly labor-intensive with very low process efficiencies of 20% or less [4]. This in turn equates to a worldwide wood consumption of 265 Mtons. Furthermore, the wood gases generated from traditional earth-mound kilns are three times higher than that of forest fires, and methane gas emission factors are of 21 g/kg of dry wood [5]. Methane's contribution to the green house effect is 20 times more damaging than that of CO_2. Other emissions include CO, NO_x, N_2O, non-methane hydrocarbons (NMGCs), and methyl chloride among others. Therefore, there is a need to design a more efficient and environmentally friendly process. Improving process design and performance by minimizing heat losses and gas emissions will ultimately increase the charcoal yield while lowering environmental impact. More charcoal yield means that less wood is required and hence fewer trees will be harvested. Similarly, higher efficiency translates to less by-product losses through flue gases and lower environmental pollution.

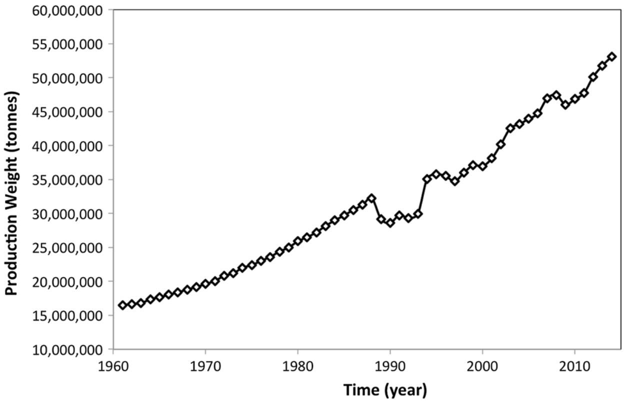
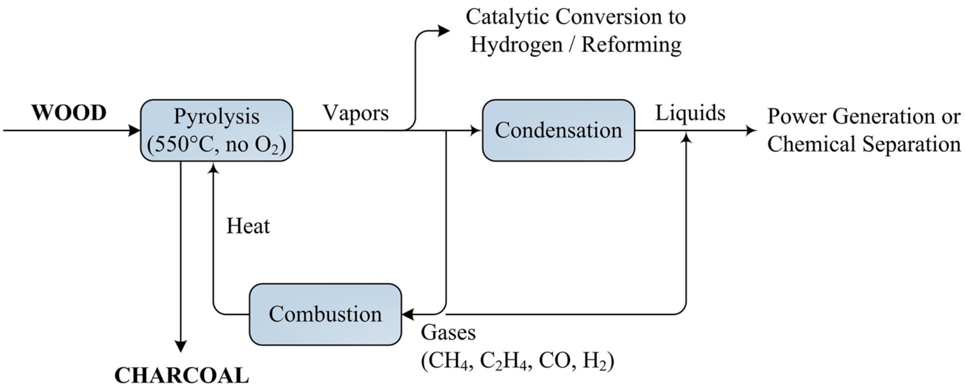


Fig. 1 Worldwide wood charcoal production in tonnes from 1961 to 2014 [3]

The production of charcoal from wood follows the principle of pyrolysis by breaking down biomass structure under intensive heat to produce gases, liquid tar and elemental carbon (Fig. 2) [6]. This carbonization process is conducted under an atmosphere free from oxygen, to avoid burning the wood into ashes, and is strongly influenced by key factors such as moisture content, retort design and process operation. The process consists of the following steps: in the drying stage wood absorbs heat and releases its moisture as water vapour at a temperature up to 110 °C; the duration of this stage is directly related to the water content present. The light volatiles removal starts at 110–270 °C while the thermal decomposition of wood starts to dominate at temperatures ranging from 270 to 400 °C. As a result, heat is evolved and the breakdown continues spontaneously provided that the wood is not cooled below the decomposition temperature. At this stage, mixed gases and vapours are driven off together with some amount of tar. As the breakdown continues, the released vapours, comprising of several combustible gases, begin to predominate as the temperature rises: carbon monoxide (CO), hydrogen (H_2) and methane (CH_4),

Fig. 2 Process flow diagram of charcoal production from wood following the principle of pyrolysis by breaking down biomass structure under intensive heat to produce gases, liquid tar and elemental carbon



together with carbon dioxide gas (CO_2) and condensable vapours such as water (H_2O), acetic acid (CH_3COOH), methanol (CH_3OH), acetone (C_3H_6O), and tars. At the completion stage, the temperature reaches 400 °C, the wood is completely carbonized into charcoal with about 30% tar contents. The carbon content in the charcoal is further increased to above 75% (by driving off tar) with additional heating and by increasing temperatures to 500–550 °C [7].

Several designs are present in the literature trying to optimize this above-mentioned process. Reed et al. described a wood-gas stove based on a new, simplified wood gasifier; gas for the stove is generated using the "inverted downdraft gasifier" principle, in one mode of operation, this stove can also produce 20–25% charcoal yield (dry basis) [8]. Antal et al. described a practical method for manufacturing high-quality charcoal from biomass that realizes near-theoretical yields of 42–62% with a reaction time of about 15 min to 2 h, depending on the moisture content of the feed [9]. Reumerman et al. developed the twin-retort carbonization process. The system was capable of producing charcoal at a rate of 900 tons per year, its efficiency was about 33% with a carbon content of 92%, and emissions were reduced at least by a factor of two [10]. Syred et al. introduced the CHaP (Charcoal, Heat and Power) process, which offers a method for producing clean efficient charcoal under pressurized conditions. The product gas from the carbonization process then drives a small gas turbine producing heat and power, this process had a charcoal yield of 38% [11]. Adam et al. built the ICPS (Improved Charcoal Production System) unit, which resulted in a yield of 30–42% and reduced the emissions to the atmosphere by up to 75% [12]. The ICPS works in two different phases; during the first phase, the ICPS operates similar to a traditional kiln; however, wood waste is burned in a separate firebox to dry the wood. During the second phase of operation, the harmful volatiles are burned in a hot 'fire chamber' thus flaring and reducing combustible volatiles. The heat gained by flaring the wood gazes is used and recycled to accelerate the carbonization process. Unlike traditional methods, the ICPS can complete a carbonization cycle within 12 h. Elyounssi et al. introduced the two-step pyrolysis process in which the first phase focuses on hemicelluloses and cellulose decomposition. During that phase, low temperatures promote char formation. At the end of that phase, the fixed-carbon yield was at a maximum. The value of the maximum was as great as that obtained under high-pressure pyrolysis and approached the theoretical value of about 60%. During the second phase of the low temperature isothermal pyrolysis, the fixed-carbon yield decreased, showing a loss of the already existing carbon. But the rise in temperature at the end of the first phase helped to preserve the value of the fixed-carbon yield at a maximum. This process helped increase charcoal quality without excessively decreasing charcoal yield [13].

The aim of this work is to develop a new design for the wood-charcoal process and test its feasibility in improving the yield and quality of the char product. Herein we report an approach to design an integrated charcoal production unit. Process simulation via computational fluid dynamics (CFD) along with a mechanical design and experimentation are combined together to develop a wood carbonization system capable of achieving high charcoal yields with minimum energy losses.

CFD Simulations

A preliminary design of the retort was modelled using Ansys Workbench - Fluent 17.2. The main purpose of the CFD simulations is to detect the distribution of the gas flow, as well as the heat transfer inside both the carbonizer and the combustion chamber. Hence, the temperature and velocity profiles were monitored inside both units.

The anticipated design for the efficient wood–charcoal retort consists of two concentric cylindrical vessels, such that wood is converted into charcoal within the inner compartment (carbonizer), while wood and agricultural wastes are burned inside the outer vessel (combustion chamber) to provide the initial necessary heat for the carbonization process. Flue gases from the combustion chamber are recirculated through a pipe into the carbonizer to help drive off moisture and increase the initial temperature in the carbonizer during startup. Furthermore, to allow for better gas circulation through the flue-gas recycle line, and accordingly into the carbonizer, an induction fan was installed at the air inlet. Figure 3 shows the design used in the simulation. ANSYS meshing tool was used to mesh the model. The resulting number of cells and nodes are 4,663,366 and 1,016,908 respectively. Maximum skewness of 0.99 occurs in a single cell. However, the overall mesh skewness is below 0.4. The dominant orthogonal quality is 0.9, except for a few elements where a minimum of $2.42e^{-04}$ is observed.

The combustion zone was modeled as a cylinder of diameter 80 cm and height 100 cm containing a heat source of 353 kW/m^3. This value is equivalent to the burning of 5 kg of wood for 5 h, based on the calorific value of wood being 14,400 kJ/Kg and the porosity of the combustor region assumed as 0.8. As for the carbonizer, it had a diameter of 50 cm and height 100 cm, and was considered to be a porous medium of porosity equal to 0.4 [14], mimicking the presence of a pile of wood. It was assumed that there is a thermal equilibrium between the fluid flow and the solid medium. The inlet to the combustion chamber is a rectangular opening where air is

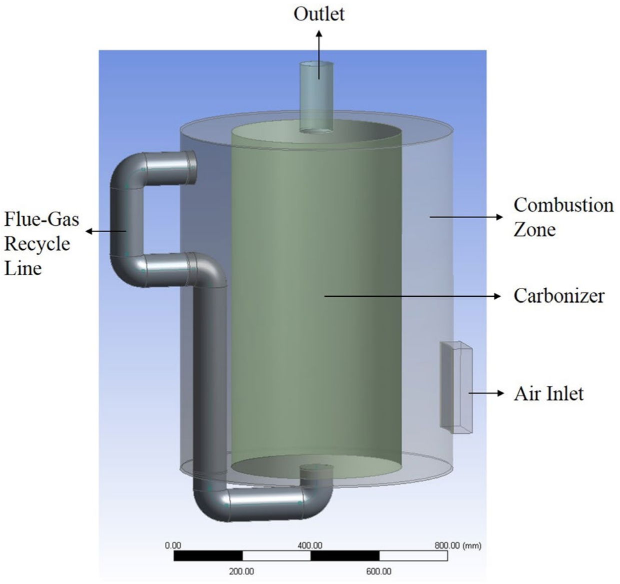


Fig. 3 Simulated retort design in ANSYS

allowed to enter. A pressure gradient of 10,000 Pa was maintained between the inlet and the outlet. This difference is desired to simulate the effect of the induction fan installed at the air inlet.

To model turbulence, the shear-stress transport (SST) k-ω model, which combines both the Wilcox k-ω and the k-ε models, was used to simulate the heat transfer and the flow dynamics inside the retort. This model is reliable for a wide class of flows (e.g., adverse pressure gradient flows, airfoils, transonic shock waves); its equations behave appropriately in both the near-wall and far-field zones. In other words, it combines the advantages of both the Standard k-ε model and the k-ω model, such that the Wilcox model is activated near the wall, while the k-ε model is implemented in the free stream. For laminar flows, the laminar zone option is enabled where flow at low Reynolds number is expected. As such, the flow inside the porous media was modeled as a laminar flow with the global model set to turbulent. This assumption is reasonable as the medium's permeability is large. Plotting the contours of Reynolds number verified the desired laminar flow in the carbonizer (Fig. 4).

To verify that the SST k-ω viscous model can be implemented to capture the turbulence with confidence, the Y+ values were checked and maintained within the recommended range, taking into consideration both accuracy and computational time. For the turbulent region, Y+ values should be between 30 and 300, while these values should be less than 5 in the laminar sublayers. In our model, Y+ values near the wall ranged between 25 and 280 where the flow is turbulent, while these values were below 1.25 for the regions where the flow is laminar.

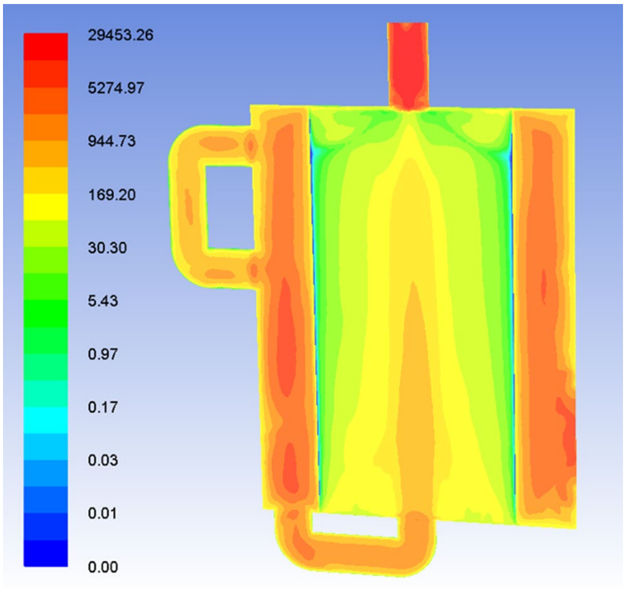


Fig. 4 Contours of Reynolds number (log scale)

Radiation was included via the P1 model, which solves an advection–diffusion equation to quantify the mean local incident radiation. This model is applicable with complex geometries having curvilinear coordinates. It is best suitable for optically thick media; however, when the optical thickness is small, it tends to overestimate the radiative fluxes from localized heat sources or sinks. As such, the P1 model can be used to appropriately capture radiation in the wood porous media. All walls in the model were set to participate in radiation.

Mechanical Design and Experimental Procedure

The retort design described in "CFD Simulations" section is built. The flue gases from the combustion chamber are conducted through a pipe into the carbonizer; this pipe passes in the combustion chamber in order to prevent major heat losses that may occur due to contact with ambient air. Based on this design, the heat produced by wood combustion is transferred to the wood in the carbonizer by a direct convection through direct contact between the flue gases and the carbonized wood and an indirect conduction through the 1.25 mm thin wall of the inner vessel. Four thermocouples and three-way valves are used in order to monitor the temperature in the different parts of the retort, and to insure that the flue gases are conducted to the carbonization vessel during the different stages. On the other hand, the pyrolysis gases were also recycled to the combustion vessel to sustain combustion and minimize the amount of wood used to generate heat. The flue-gas recycle line was used for drying the wood at the initial stage only and it is closed thereafter. The main idea here is having the carbonizer in the center to achieve high temperatures. Manipulating the valves around the carbonizer can either introduce flue gas for drying wood at startup or for recirculating generated methane into the combustion zone. The carbonizer has both inlet and outlet pipes as shown in Fig. 5 to allow for switching between drying, no drying, methane recirculation into the combustion zone and methane flaring. Traditional kilns are not well insulated and have major heat losses during the long period of operation due to wet soil covering the hot wood and charcoal. In our design, a rockwool insulation that can sustain temperatures up to 1000 °C was used. Such insulation is used in order to minimize heat losses and decrease energy consumption during the carbonization process. (See Figs. 5, 6, 7 for design annotations of valves, thermocouples and insulation, and the interior of the design).

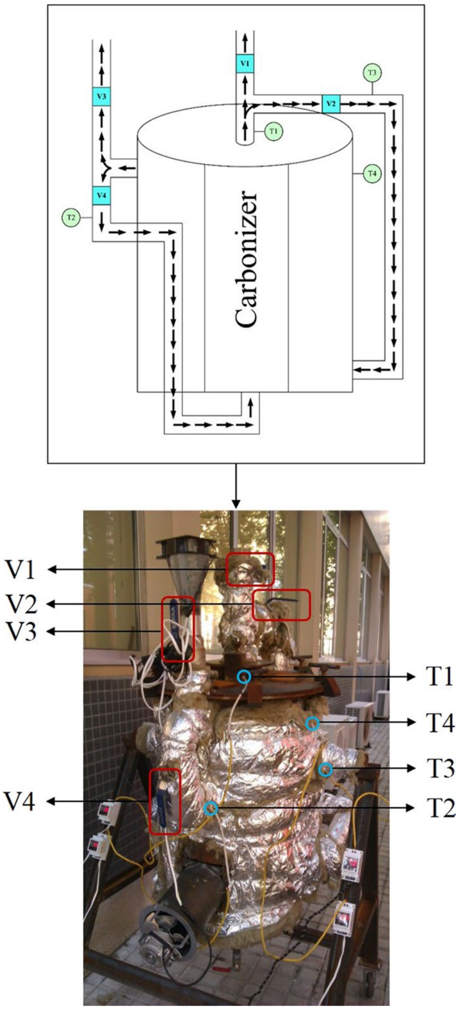


Fig. 5 Valve and thermocouple locations in the built design. Valves: Valve *V1* directs the carbonization gases to the outside. Valve *V2* directs the carbonization gases to the recycle line. Valve *V3* directs the combustion gases to the outside. Valve *V4* directs the combustion gases back to the carbonizer to initially dry the wood (flue-gas recycle line). Thermocouples: Thermocouple *T1* monitors the temperature inside the carbonizer, *T2* monitors the temperature inside the flue-gas recycle line, *T3* monitors the temperature inside the recycle line and *T4* monitors the temperature inside the combustion chamber

Similarly to the production process described in the introduction, the wood was initially dried, followed by raising the temperature to 270 °C initiating spontaneous carbonization. A final heating above 500 °C was performed to drive off tar and increase the fixed carbon contents. Each experiment was performed in triplicates to prove the ability of the constructed prototype. Different batches of 5 kg oak wood with different moisture contents were used as raw materials. The produced charcoal samples were taken after achieving each experiment and analyzed according to ASTM D 2016-74 standards in order to specify the composition of each charcoal sample.

Results and Discussions

CFD Simulations

In order to assess the applicability and efficiency of the proposed retort design, a CFD simulation was carried out to monitor both velocity and temperature profiles. The first main concern was to track the gas flow from the outer vessel (combustion zone) into the inner carbonizer through the flue-gas recycle line, to dry the wood before the onset of carbonization. It was suspected that the gas would choke and consequently extinguish the process. However, the results of simulation show that no choking or backflow have occurred inside the carbonizer and the flue-gas recycle line (Figs. 8, 9), which was a key condition to guarantee the operation of the proposed design. Figure 8a shows that the velocity in the flue-gas recycle line ranges between 0.006 and 0.03 m/s while Fig. 8b reveals that the velocity in the carbonizer is mostly 0.18 m/s with a maximum of 40 m/s occurring at the outlet due to the pressure gradient. Air enters through the inlet at the bottom right of the combustion zone (Fig. 8b) at a velocity of 4 m/s. In addition, the streamlines in Fig. 9a,b indicate the path followed by air entering at the inlet to the combustion zone and to the carbonizer through the recycle line to finally exit both chambers from the outlet.

The second concern was the temperature profile inside the retort. The results reveal a maximum value of 565 °C inside the combustion chamber away from the air inlet (bottom right), where air enters at ambient temperature (26 °C). As for inside the carbonizer, the prevalent temperature is about 300 °C; the uniformity of the distribution is affected by the air inlet cooling the combustion zone from the right side (Fig. 10). However, higher

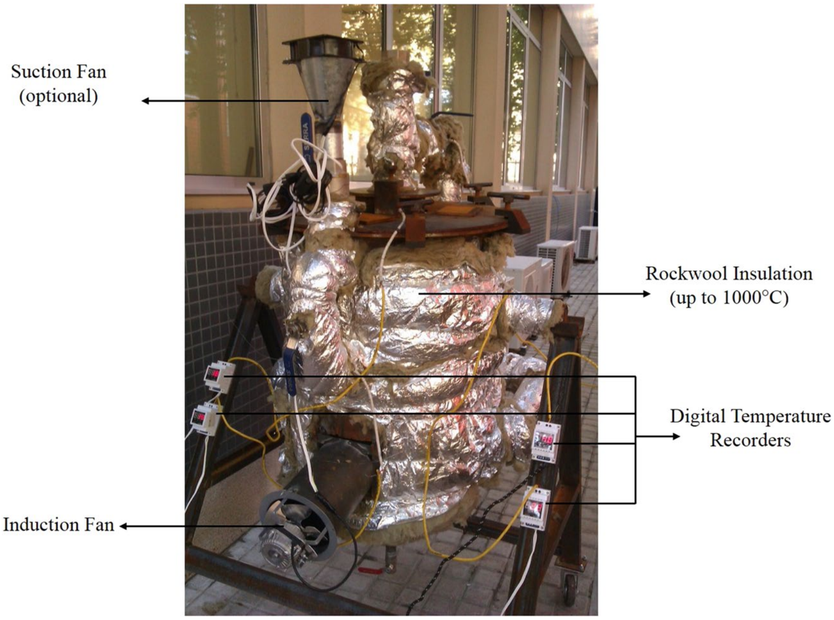


Fig. 6 The designed retort showing induction and suction Fans, Rockwool insulation and four digital temperature recorders


Recycle Line

Tars Container

Split at Flue-Gas Recycle Line

Fig. 7 Different components of the built prototype

temperatures are required for pyrolysis to occur. Therefore, based on the simulation results, the proposed design was further modified, since there was an indication of a potential incomplete combustion. A methane recycle line was added from the carbonizer outlet in order to increase the temperature in the combustion zone (Fig. 5, valves V1 and V2). Furthermore, the pipe of the flue-gas recycle line that introduces the combustion gases into the carbonizer (Fig. 5, valve V4) was split at the bottom. This is expected to provide better heat distribution at the inlet of the carbonizer. Finally, a tar container was placed at the bottom of the retort.

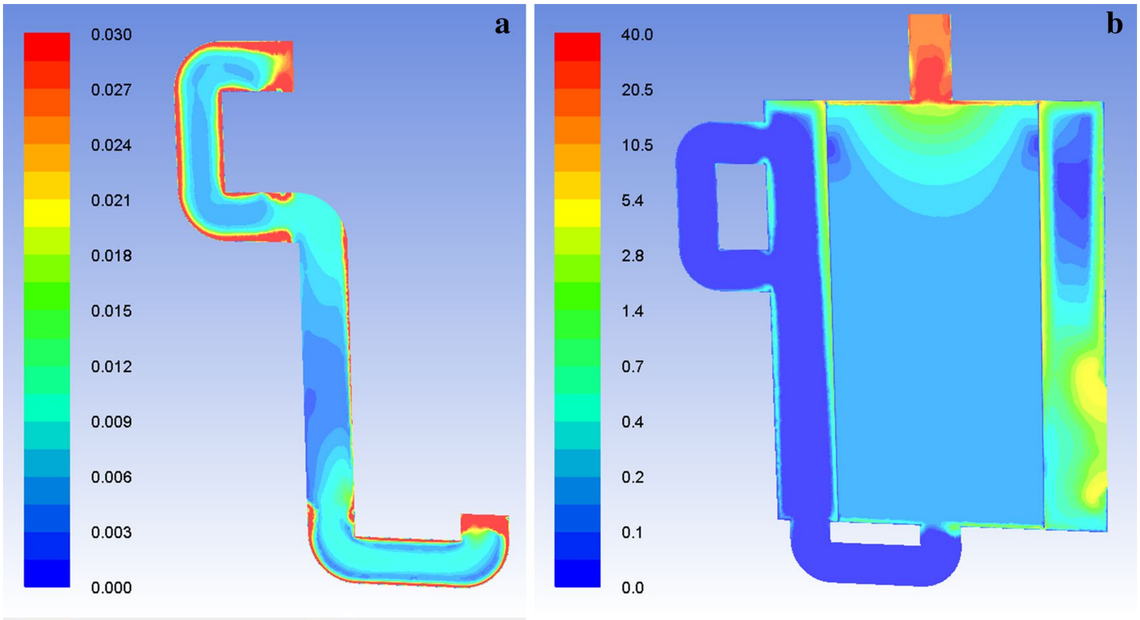


Fig. 8 Velocity contours (m/s) (log scale). **a** In flue-gas recycle line, **b** in combustor and carbonizer

Experimental Results

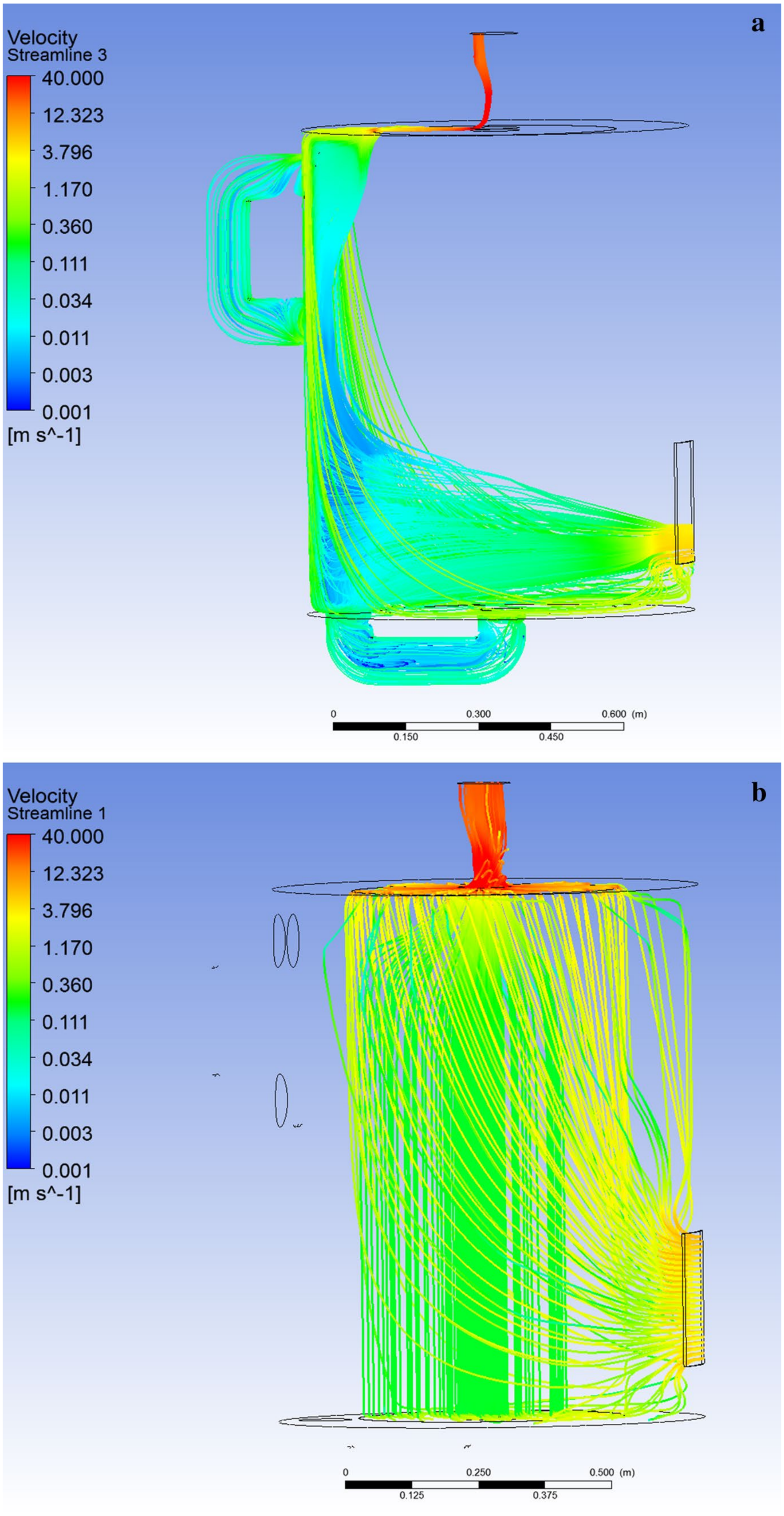
The system was successfully tested after implementing the modifications in the design. The temperature inside the carbonizer peaked in 20 min to 900 °C (at 75 min from t = 0) (Fig. 11). During this time period, the recycle line was opened (valve V2) to allow the carbonization gases to enter the combustion zone. The temperature inside the combustion chamber increased gradually due to the presence of combustible gases especially methane. Figure 11 shows the temperature profiles recorded from the thermocouples and the details of the performed valve operations. The temperature of the carbonizer becomes eventually higher than the combustion zone especially when methane is generated during pyrolysis/carbonization reactions (to form charcoal). Achieving a high peak temperature helped in driving off more volatiles and decreased tar contents. The produced charcoal had better quality with higher carbon contents. The adopted adjustments of the design eventually yielded a higher temperature distribution as expected.

Tables 1 and 2 show the overall process efficiency and the charcoal analysis results at carbonization temperatures ranging from 550 to 900 °C. The process operated at 550 °C showed the highest charcoal yield on dry basis (Y_d) of 46% with carbon content of 73% achieved in 1 h and 15 min. However, when operating the retort at 900 °C, a lower yield (37%) and a higher carbon content (87%) and operation time (2 h and 50 min) were observed. Therefore, increasing the process temperature produced more volatiles resulting in a yield decrease while increasing the carbon content in the product. The control of the process temperature directly affects the product quality and helps in tailoring the product according to required specifications by the user.

The overall process duration was marginally reduced to a few hours as illustrated in the tables below. It is anticipated that increasing the degree of conversion of wood to charcoal will have a direct effect on limiting wood harvesting. This will save trees from deforestation, while the decrease in process time will certainly lead to savings in labor costs making the whole operation more economical. A traditional kiln operating at 20% efficiency would consume 5 kg of wood (or biomass)/kg of charcoal produced. Increasing this efficiency to 46% would need 2.17 kg of biomass/kg of charcoal produced, hence reducing biomass consumption by 2.83 kg/kg of charcoal. If all the charcoal produced worldwide achieves such efficiency, consumption of wood would be reduced by more than 100 Mtons/year.

By comparing this design against literature data, it is shown that the suggested retort is producing higher yields than most published designs (Reed et al. 1996; Reumerman et al. 2002; Syred et al. 2006; Adam et al. 2009) including traditional production methods. Our yield lies within the range obtained by Antal et al. (1996), but below the 60% yield reported by Elyounssi et al. (2010). However, the simplicity of the proposed design involving a single stage process instead of two is an advantage in terms of cost and operation. One should also take into account that the type of biomass used and feedstock can have a high impact on the process yield. The quality and quantity of each type of product depends on the operating parameters, such as the

Fig. 9 Plot of streamlines (m/s) (log scale). **a** Inside flue-gas recycle line and combustion zone, **b** inside carbonizer and combustion zone



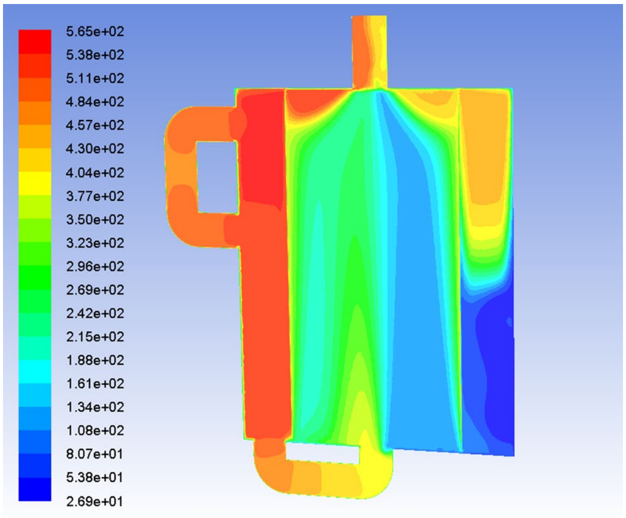


Fig. 10 Contours of static temperature (°C)

reactor design, operating temperature and heating rate, and type of feedstock [14–16]. Table 3 compares our design with published results showing in each case the production method used and the charcoal yield achieved.

Table 2 Charcoal product analysis measured according to ASTM D 2016-74 standards

T (°C)	Moisture (%)	Volatiles (%)	Ash (%)	C (%)
550	4.2	18.4	4.3	73.1
650	2.6	14.9	4.9	77.6
900	1.1	6.2	5.3	87.4

Conclusion

A compact retort with integrated operation was designed via analysis of the heat transfer mechanisms and fluid flow dynamics using CFD – ANSYS Fluent. The mechanical design applied heat integration with simultaneous preheating to maximize the process heat efficiency. The experimental work led to producing charcoal efficiently and in a relatively short period. The results showed a major increase in the charcoal process yield reaching 46% on a dry basis. This is an improvement in comparison to traditional methods and most of reported designs. The designed unit resulted in a decrease in the production time, to less than 3 h depending on the operation temperature and water

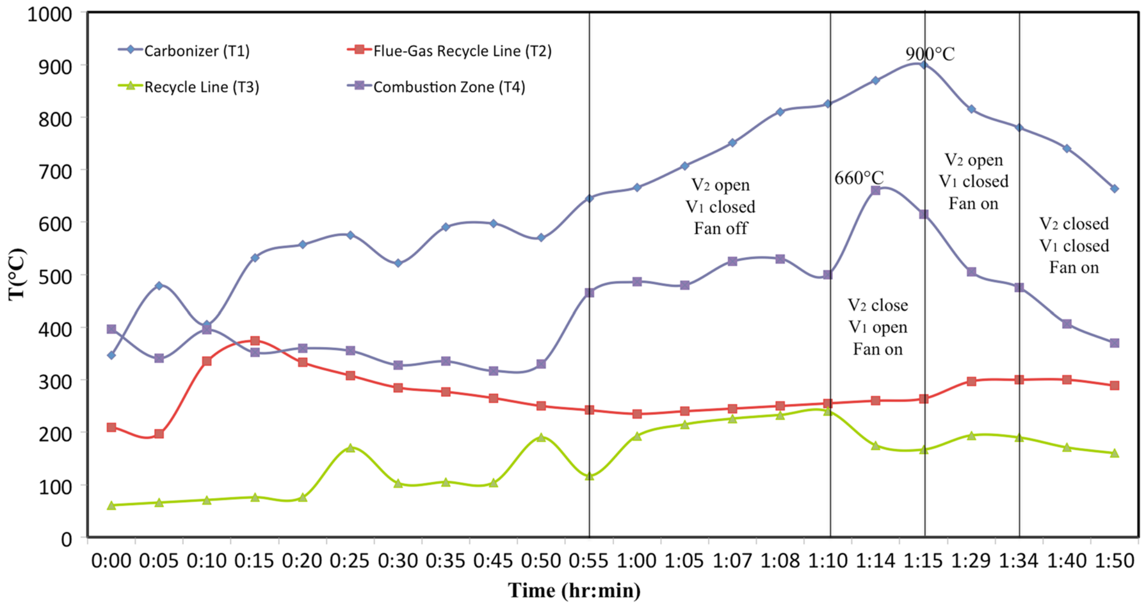


Fig. 11 Temperature profiles recorded by thermocouples T1, T2, T3 and T4 and valve operations performed

Table 1 Experimental conditions and averaged results based on experiments performed in triplicates (Wt = weight, w = wet, d = dry, p = product, Y = yield). Yield standard deviation ranges from 5 to 10%

T (°C)	$Wt._w$ (kg)	$Wt._d$ (kg)	$Wt._p$ (kg)	Y_w (%)	Y_d (%)	t (min)
550	5.79	5.05	2.32	40	46	75
650	4.79	4.39	1.81	38	41	135
900	5.42	4.97	1.84	34	37	170

Table 3 Charcoal yield (%) comparison of different designed processes

Production method	Charcoal yield (%)	References
Gas generation using the "inverted downdraft gasifier" principle, in one mode of operation	20–25	Reed et al. [8]
Pyrolysis is accomplished at elevated pressures in a stagnant gas environment	42–62	Antal et al. [9]
Twin-retort carbonization process	33	Reumerman et al. [10]
CHaP (charcoal, heat and power) process	38	Syred et al. [11]
ICPS (improved charcoal production system) unit	30–42	Adam et al. [12]
Two-step pyrolysis process	60	Elyounssi et al. [13]
Partial combustion in charcoal kilns	40	Saravanakumar et al. [17]
Biomass carbonization system using microwave heating	31	Payakkawan et al. [18]
Two-step process slow high temperature pyrolysis	20–28	Solar et al. [19]
Two-concentric cylindrical retort	46	Suggested design

content of the feed, while maintaining a good quality of charcoal at high carbon contents of about 80%. With current worldwide charcoal wood consumption of 265 Mtons, the suggested design could save more than 100 Mtons of wood annually and reduce greenhouse emissions by 42 Mtons/year.

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