AMERICAN UNIVERSITY OF BEIRUT

TOWARDS AN ENVIRONMENTALLY CLEAN CHARCOAL PRODUCTION

by
RACHAD MOKDAD

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RACHAD MOKDAD

Approved by:

Dr. Joseph Zeaiter, Associate professor — Advisor
Department of Chemical and Petroleum engineering

Dr. Kamel Abo Ghali, Professor — Member of Committee
Department of Mechanical Engineering

Dr. Mohammad Ahmad, Professor — Member of Committee
Department of Chemical and Petroleum Engineering

Date of thesis defense: January 28, 2019

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AN ABSTRACT OF THE THESIS OF

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The aim of this research is to develop a sustainable process for a compact integrated wood charcoal retort. To assure efficiency and productivity, the design was first investigated via CFD simulations to monitor the temperature and velocity profiles inside the retort. The final compact design is formed of a double vessel arrangement where the wood is carbonized in the central vessel (i.e. carbonizer) and the outer vessel is the combustion furnace. A flue-gas recycle line leaves the furnace to preheat and dry the wood in the carbonizer during startup. This developed design allows the syngas/methane coming out of the carbonization process to be re-circulated into the combustion furnace to provide the necessary energy and to assure the sustainability of the process. The integrated compact retort is then tested experimentally, and as a result, only 2-3 hours were needed to achieve complete carbonization of oak wood. Different temperatures are achieved during operation with a maximum of 900 °C reached. The charcoal yield ranged between 37% and 46% on a dry basis, and the charcoal carbon contents were between 73% and 78%.

CONTENTS

ILLUSTRATIONS

TABLES

CHAPTER I

INTRODUCTION

A. Aim of this research

Increasing charcoal yield can be done by improving process design and overall performance by reducing heat losses and gas emissions, and hence, lessening any negative environmental impact. Attaining a better charcoal yield is a target that we should aim for since having more charcoal yield means that less wood is required for the process to be carried out thus fewer trees. similarly, higher efficiency means less by-product losses through flue gases, thus lowering as much as possible environmental pollution.

The aim of this research is to develop an efficient process that would be able to achieve high charcoal yield, while minimizing energy usage and reducing environmental emissions.

The inclusion of system design combined with heat integration, will be applied together to optimize process design, leading to minimum heat losses and maximizing wood conversion to charcoal. It is expected that this approach will contribute in reducing deforestation and environmental pollution caused by charcoal production.

B. Research Methodology and structure:

This thesis will be structured as follows:

Chapter **two** deals with the literature review where we conduct a critical review in the literature of recent experimental developments and processes with an in-depth focus on challenges and limitations faced by different researchers in this field. The outcome from this task will define procedures for experimental and equipment design

Chapter **three** describes the proposed retort design, where we conduct CFD simulations in order to identify the optimum design. By simulating the flow and the heat transfer inside the retort, we can have an idea about the temperature and the velocity profile inside the unit. Then based on the CFD results, a laboratory prototype unit was built.

Chapter **four** presents the experimental work and results where we Carry out laboratory experiments to analyze process behavior and dynamics: The stage of wood carbonization to charcoal is a step-wise procedure where the mechanism of wood structural breakage evolves over a wide range of temperature. Given the variety of operating conditions, extensive laboratory work was necessary to optimize process conditions in terms of key operating variables such as temperature, time and yield.

Chapter **five** concludes the research where we summarize the research findings and give recommendations for future work.

C. Importance of charcoal

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 50 Mtons in 2017 [3] as shown in Fig. 1. This is equivalent to a minimum energy output of 52 gigawatts per year. Brazil continues to be ranked number one at 6.25 Mtons or ~6.54 gigawatts per year, followed by Ethiopia and Nigeria at 3.2 and 2.2 MTons successively (i.e.5.6 gigawatts both 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-

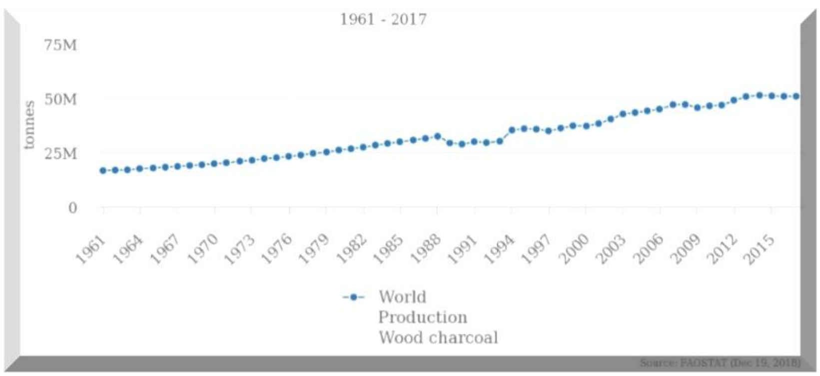

Figure 1: Worldwide wood charcoal production in tons from 1961 to 2017 [3]

intensive with very low process efficiencies of 20% or less [4]. This in turn equates to a worldwide wood consumption of more than 250 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 greenhouse effect is 20 times more damaging than that of CO2. Other emissions include CO, NOx, N2O, 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 byproduct losses through flue gases and lower environmental pollution.

D. Charcoal production process

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 knowing that fresh/green wood may contain up to 50% water. The light volatiles removal starts at 110–270 °C, where dry wood starts to give off carbon monoxide, carbon dioxide, acetic acid and ethanol; while the exothermal 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), 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].

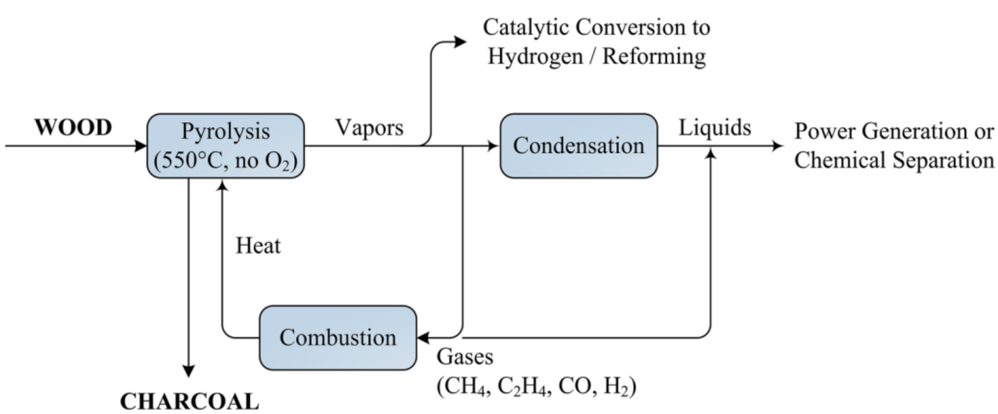

Figure 2: Schematic diagram of wood pyrolysis into charcoal and fuel

CHAPTER II

LITERATURE REVIEW

A. Traditional charcoal production

Since the dawn of history, man has found different methods for charcoal production that are now considered traditional. Earth was used as an armor against oxygen and as an isolator for wood carbonization.

We can differentiate between two methods for using an earth barrier as a sealing in charcoal making [8], one is the pit or kiln method and the other is the mound or pine method. Both methods share common and negative points; they are both: labor intensive, time consuming and have a low carbon yield. Below, each of them is described and explained separately.

1. The kiln method

First, for the startup of the process, the pit is excavated and then wood logs are loaded. To improve the volumetric efficiency as much as possible, gaps between wood must be filled with smaller woods or branches. Then, the pit is covered with scrapped earth to seal up the chamber. To make sure that wood is properly heated and ready for carbonization, the hot gas passes along the floor of the pit by disposing the charge on a crib of logs. The pit is illuminated at one end; the gas generated by this fragmentary burning of wood that is charged will slowly dry out the earth, that leads to increasingly heat losses until heating up the rest of the wood to attain the carbonization point measures around 280°C.

In large pits, the carbonization process might take up to 30 days for its completion. During carbonization, the earth covering the pit, might sink and then creating holes and cracks which must directly be closed not to cause air leakage. When this stage is completed the pit is exposed to cooling which is expected to take several days, depending on the weather.

2. The mound method

According to FAO [9] The mound method process is the same as the pit process, but what differs between both is that in the pit process, the pit is turned over but in the mound method, the wood is stacked above the ground and covered with earth. For rocky and shallow soils, it is recommended to use the earth mound instead of the pit especially for cases where the water table is close to the surface. Plus, a mound site is permanent which means that it can be used several times whereas pits are used few times and them they are replaced by new ones that will follow the timber resource.

B. Industrial charcoal technologies

Far from traditional technologies, new ones appeared in charcoal making. Among them, we can distinguish the retort technology, along with several types of retort so far. All the designs listed below from section B-1 to section B-8 are referenced from Centre for

Research and Technology Hellas Institute for Solid Fuels Technology and Applications (CE.R.T.H. / I.S.F.T.A., May 2004) [10], Their principal designs can be classified based on the physical characteristics of the retort, as follows:

1. Vertical retorts

Vertical retorts hold many different carbonization devices, relatively more than any other arrangement, and include both, batch, and continuous types. In vertical retort processes, either a batch or continuous type, the coal is always charged at the top likewise for high-temperature coke oven, but discharge is usually from the bottom. Retorts have relatively small capacities. This is mainly due to the very low thermal conductivity of both the coal and char. Furthermore, penetration of heat through the layers of these materials into the center of the charge is slow, retorts that are indirectly heated by conduction of heat through the retort walls are generally narrow. To increase the rates of both, the heat transfer and the carbonization, some retorts are made of steel materials while in others, the internal heating was adopted. While circulating hot gases through the retort, internal heating is highly affected: either the product gases of fuel combustion or the carbonization preheated gases.

Construction materials for vertical retorts range from steel to other refractory materials such as: Silica brick, high alumina refractories, magnesite refractories, chromite refractories, zirconia refractories and much more. Higher temperatures are used to speed up the carbonization of the charge are applicable with refractory retorts. Similar methods of heating, either direct or indirect or a combination of both are used with refractory and non-refractory materials.

2. Fixed bed retorts

a. Indirectly heated fixed bed retorts

Indirectly heated fixed bed retorts consist essentially of chambers. These chambers are indirectly heated, and this is done by circulating the products derived from the fuel gas combustion through channels that are built in the wall. To obtain a satisfactory rate of production, retorts must be much narrower in width than coke ovens, and this is because of the low temperatures and the slow rate at which carbonization proceeds.

The main typical processes that take place in indirectly heated fixed bed retorts are:

- Krupp-Lurgi process
- Brennstoff-Technik
- Cellan-Jones ovens
- Carmaux process
- Otto retort
- Weber process
- Phurnacite process
- Parker retort

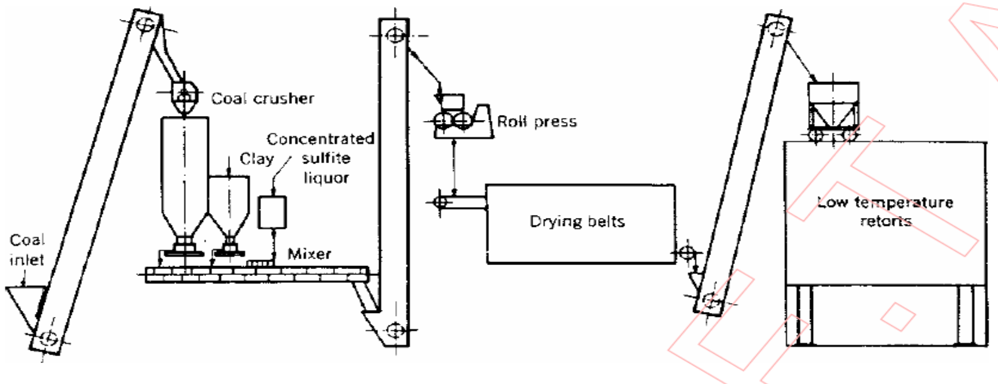

Figure 3: Weber Process [10]

b. <u>Directly heated fixed bed retorts</u>

In addition to the fixed bed retorts which are heated by transmission of heat through the walls, several other retorts have been developed in which carbonization is carried out by direct contact of the coal with hot gases such as:

- Rexco process
- Records "Coalene" retort
- Karrick retort.

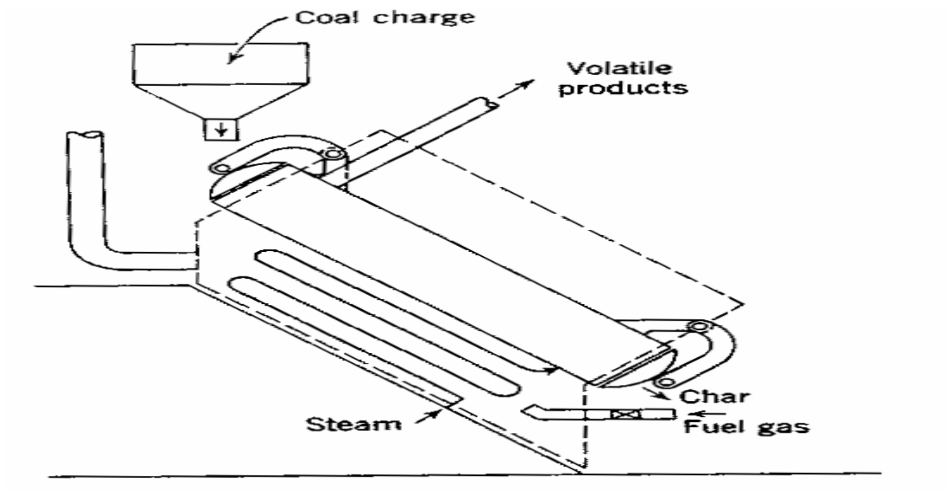

Figure 4: Records carbonisation retort [10]

3. Continuous vertical retorts

Continuous vertical retorts operate with coal charged continuously on top of it and char removed at the base. For carbonization to be complete by the time the coal reaches the base, the height should be sufficient. Retorts are shaped in different ways: some of them are narrow chambers like slot ovens while others are round-shaped or ellipsoidal.

Continuous vertical retorts have been heated in several ways: either direct combustion or indirect combustion. In direct combustion, continuous vertical retorts are heated through the means of hot gases ascending through the coal charge, while in indirect combustion, hot combustion gases pass through flues in the retort walls.

Once indirect heating alone is applied, confined slot-type ovens or thin layers of coals have been required. In this method, hot gases, or steam at the base of the retort have been added to several methods for heating retorts.

When hot gases are introduced in the retort, they accelerate the carbonization of the charge and this is followed by generating heat up uniformly through the mass of descending coal. Once the coal is carbonized after direct contact with the hot gases, the cross-sectional area of the retort would be greatly larger than it would be if it is indirectly heated. The hot gases that are introduced for direct heating of the retorts include the products generated by the combustion of fuel gas, steam or product gas that were recirculated after preheating has been made.

Retorts that use steam or product gas have been usually indirectly heated as well. When hot gases are introduced directly, volatile products generated by the carbonization process are mixed together with the heating medium, and additional provision is required in the gas processing equipment to cool this much larger volume, along with treating it to separate the tar. If steam is used as the heating medium, the treatment becomes a simple one. Once the mixture of gases is cooled, the steam is condensed and becomes ready to be separated from condensed tar by phenomenon of decantation. Many factors affect the overall heating value. Between them, the presence of products generated by combustion in the final mixture of product gas from a retort, obviously lowers the material heating value of the retort even though its overall heating content will not be modified. As a fuel, a lean gas is less desirable than the higher heating value gas, since it can be produced without the dilution from products of combustion.

Examples of continuous vertical retorts that are directly heated:

- Lurgi-Spulgas retort

- National Fuel process
- Pintsch-Weber process
- Electrically heated retort

Examples of continuous vertical retorts that are indirectly heated:

- Petit retort
- P.D.P retort
- Stansfield retort
- Archband “Pipestem” retort
- Geissen retort
- Borsing-Geissen retort
- Heliopore process

Examples of continuous vertical retorts that are directly and indirectly heated:

- Koppers continuous vertical ovens
- Didier-Werke retorts
- Rochdale process

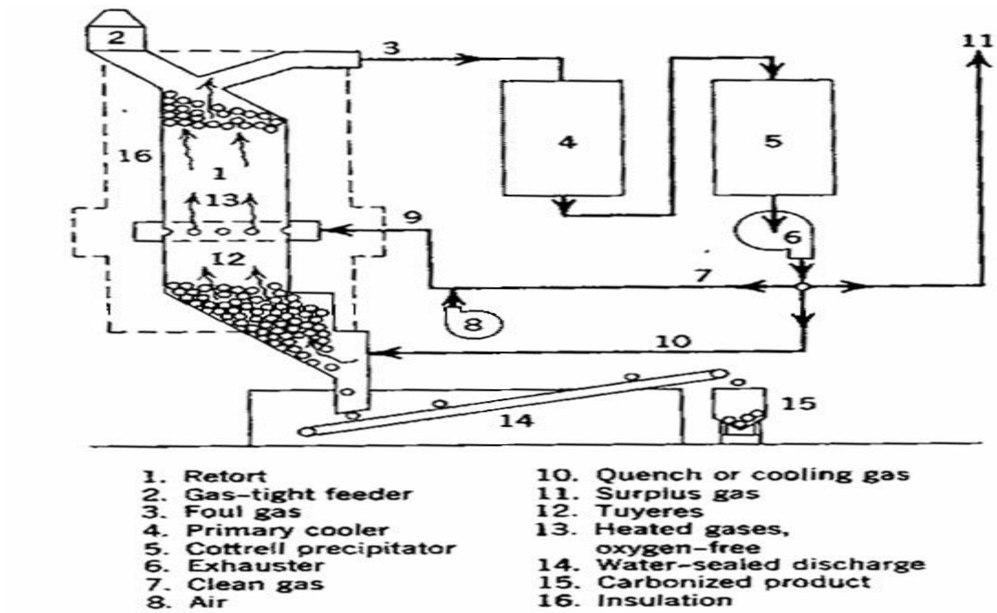

Figure 5: Flow sheet for the National Fuel Process [10]

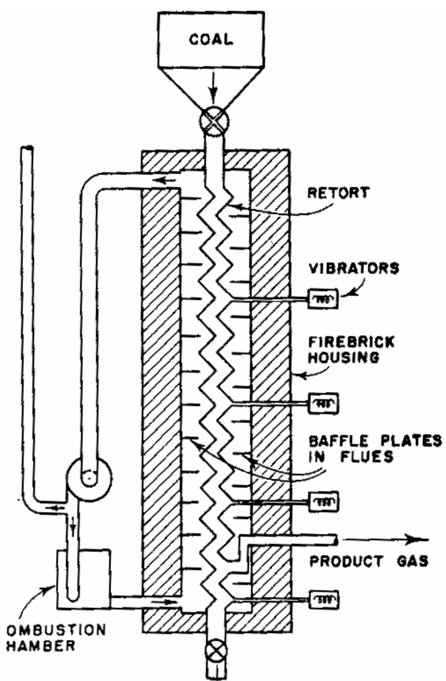

Figure 6: Cross section through Petit retort [10]

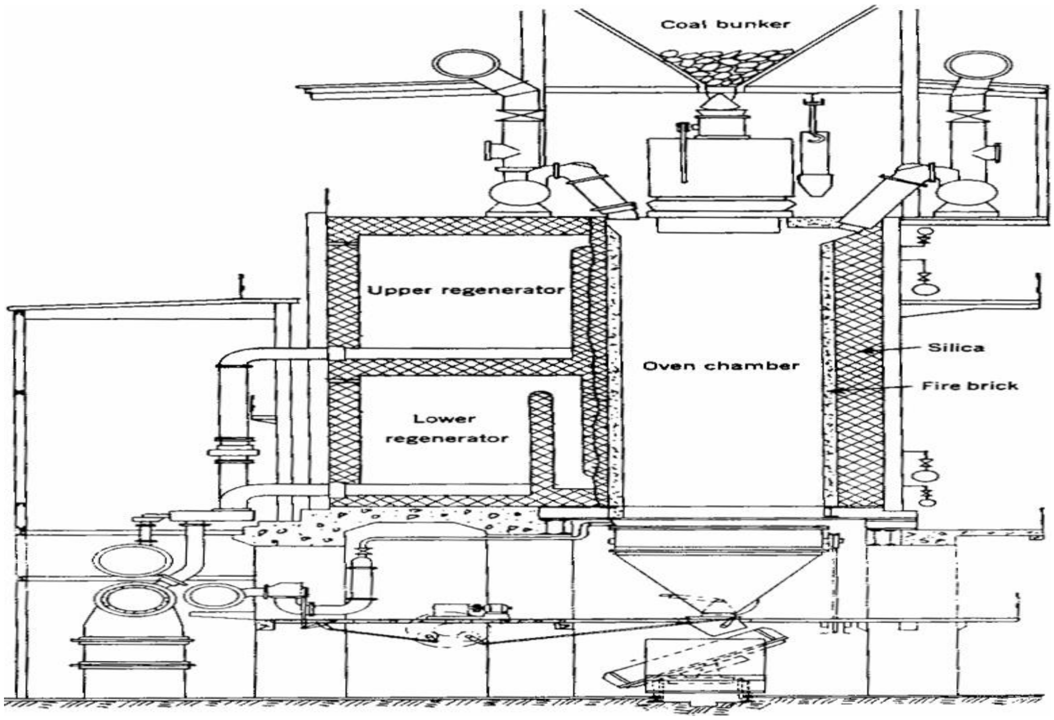

Figure 7: Koppers continuous vertical oven [10]

4. Fluidized or entrained carbonization

Finely divided char that are products of the carbonizing fine coal while fluidized by a stream of heated gas could be useful for boiler firing. To maintain the solids in the fluidized state, the fluidized retort contains a bed of coal and char through which a gas is passed. While gas is passing through, coal is added, and char is withdrawn continuously.

In an entrained process, on the other hand, the coal introduced into a stream of gas is carried through the retort into a separator.

Fluidized or entrained retorts adapt adequately to the continuous processing of large tonnages of coal, and the availability of much useful experience on their design and operation is available to the industry from the large-scale applications of fluidized processing in other fields, typically as in petroleum refining.

Therefore, fluidized processes for the carbonization of fine coals specifically have been attracted considerable concern, and further research is being proceeded in laboratories all over the world.

Examples of fluidized processes are:

- United Engineers and Constructors process
- Singh process

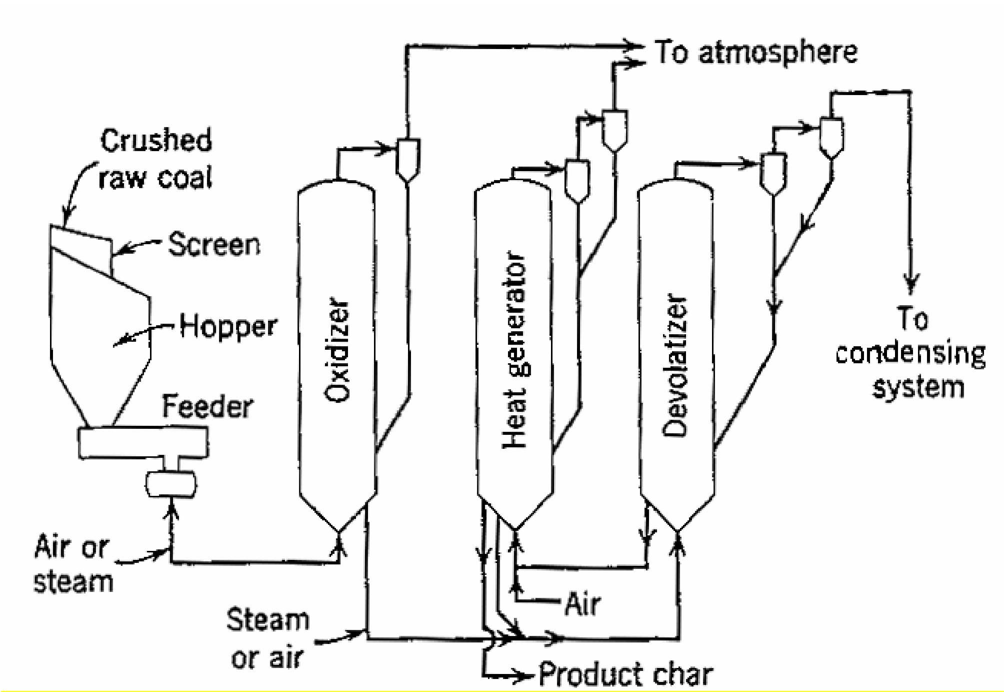

Figure 8: Singh process [10]

5. Horizontal retorts

Horizontal retorts hold essentially a long steel vessel, often cylindrical, through which the coal is moved as carbonization happens along the process. Horizontal retorts basically differ from other forms in its methods employed for transferring the heat of carbonization to the coal charge. The most common heating medium has been hot combustion gases, which have been practiced indirectly by external heating of the shell, and this is done directly by passing the hot gases, through the retort in contact with the coal, followed by a combination of both methods. To wrap a rich product gas undiluted with combustion gases, the product gas has sometimes been heated several times and recycled through the retort in direct contact with the coal.

Cylindrical retorts have two possible ways of being added: they can either be rotated or fixed. In order to keep the coal moving along the retort, the longitudinal axis of a rotated cylindrical retort is inclined on a frequent basis a few degrees to the horizontal, along with coal feeding at the higher end and the char is removed at its lower end. Fixed horizontal retorts are supplied by a screw or paddle device, which by rotation conducts the coal and char from the entrance to the outlet of the retort.

Continuous horizontal retorts can be divided into two categories: indirectly and directly heated.

Examples of indirectly heated horizontal retorts:

- Disco process
- Hayes retort
- Mimura carbonizer

- Wanishi carbonizer

Examples of directly heated horizontal retorts are:

- University of Kentucky process
- Humboldt sand carbonizer

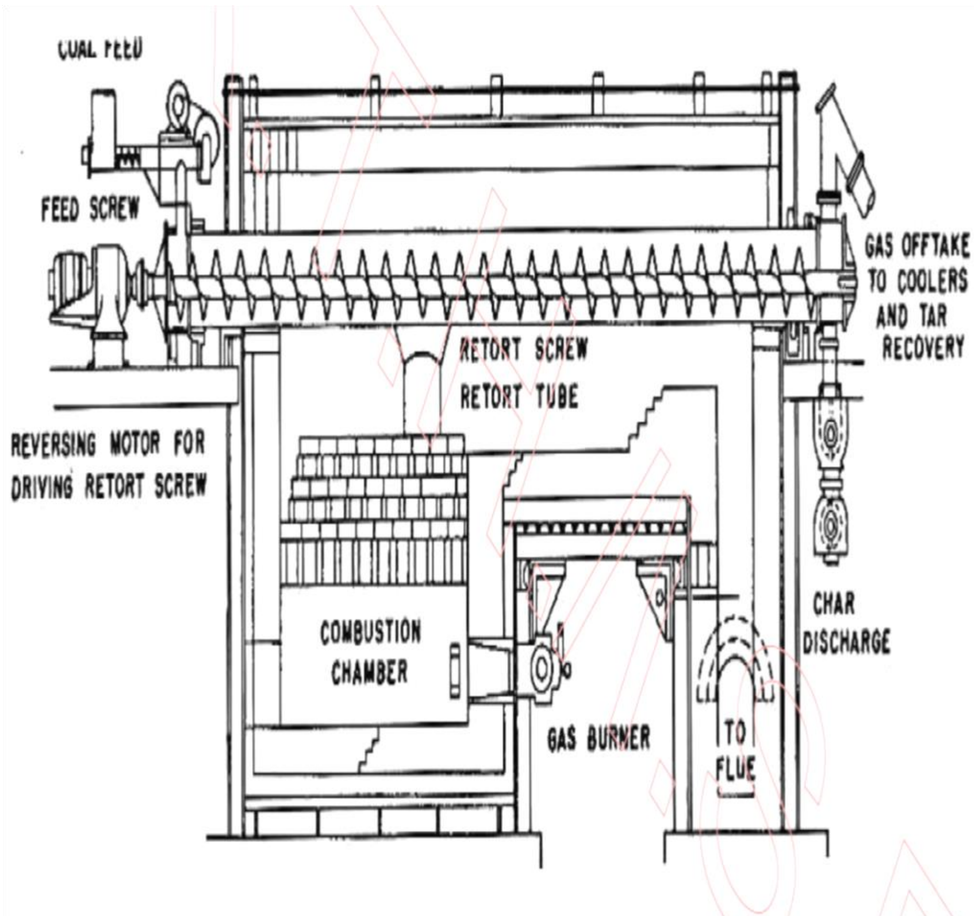

Figure 9: cross section of a Hayes horizontal retort [10]

6. Fixed horizontal retorts

Several assemblies are mandatory to conduct the coal through fixed horizontal retorts: rabble arms, screws, or other device. Fixed horizontal retorts are shown up to have been used for a more limited extent than rotating tools have.

Some examples are:

- Shimomura retort
- Cotarco retort

7. Conveyor retorts

In conveyer retorts, the coal is carbonized continuously during its advance through a fixed horizontal duct while spread out on a conducting surface.

Conveying retorts have some restraints: the moving parts of the conveyor are exposed to the temperature conditions in the retorts, and the coal should be spread out in thin layer. Therefore, coal capacities are relatively low. For industrial production of char and coke, we aim for using coking stoker units, which are examples of giving relatively high capacities. In these units, the coal is simultaneously carbonized to produce a char or a coke, and the heat of combustion of the volatile product along with the allocation of the coal itself is utilized in boiler firing.

Some examples of processes taking place in conveyor retorts:

- Coking stoker
- C.W. & F. process

- Flatbed retort
- Storrs process

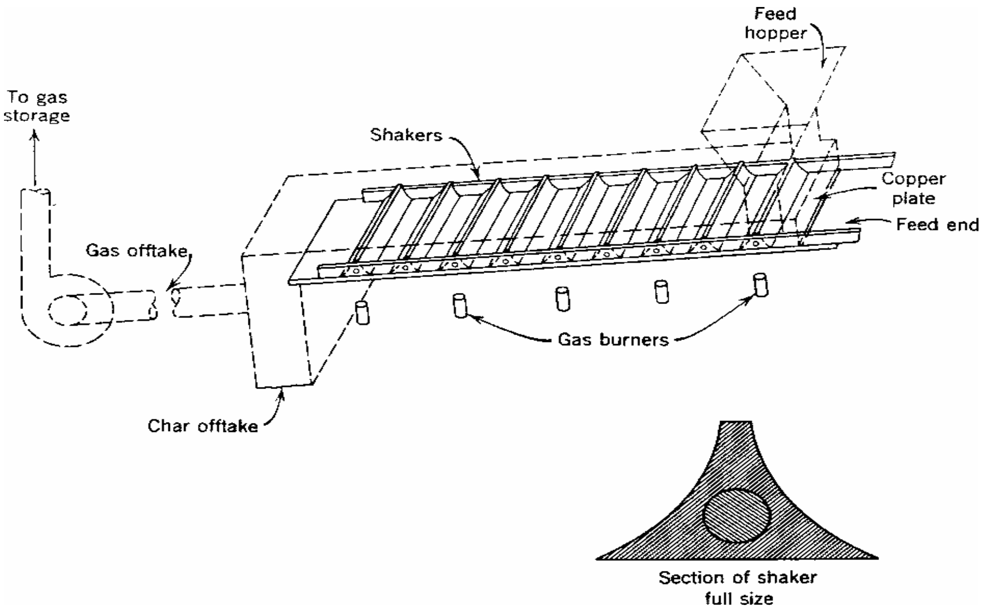

Figure 10: Schematic of Flatbed retort [10]

8. Tray retorts

These are retorts consisting of horizontal trays mounted in a vertical shell and resembling Nichols- Herreshoff furnaces. These are among the devices used for carbonizing coals.

Examples of processes taking place in tray retorts are:

- Baumco process
- Buttner retort

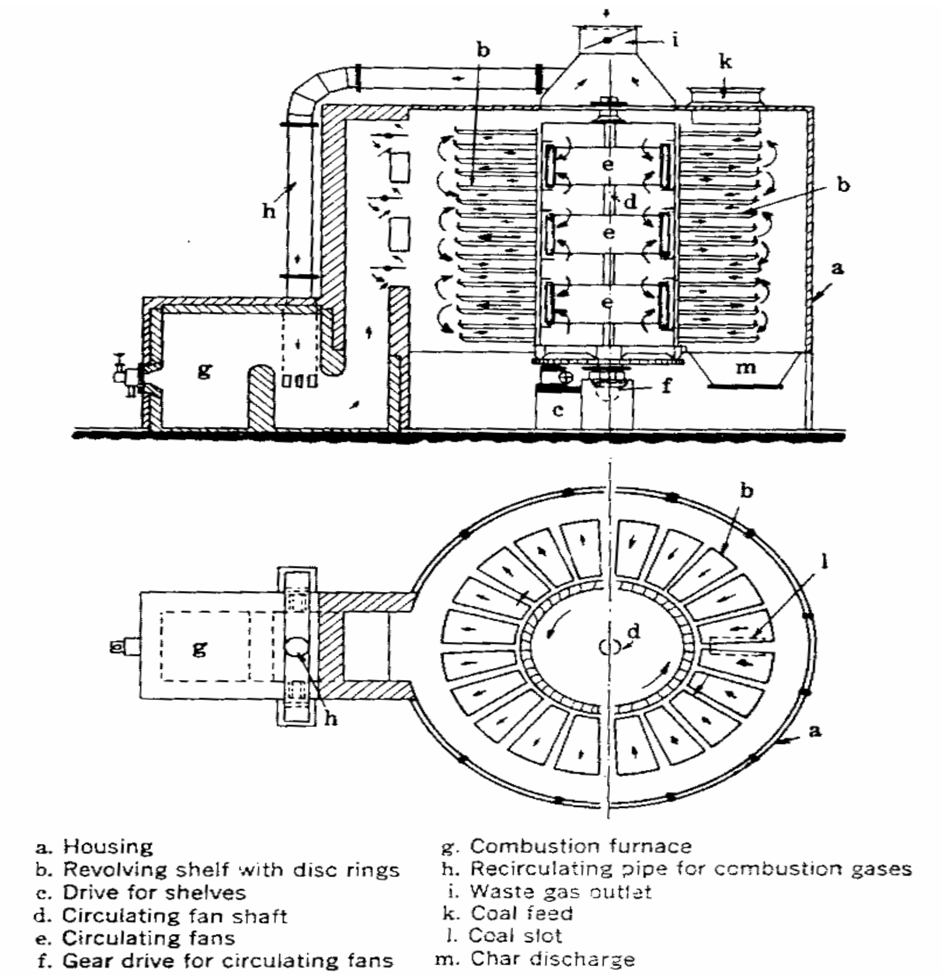

Figure 11: Buttner retort [10]

C. Recent researches

In 1996, T.B. Reed and Ronal Larson [11] described a wood gas stove that was based on a new, simplified under the name of wood gasifier. The gas for the stove is generated using what is called the inverted downdraft gasifier principle, and on a one mode of operation, this stove is able to produce 20-25% yield charcoal on dry basis.

Also in 1996, Antal and al. [12] described a practical method for the manufacturing of high quality charcoal from biomass that realizes near theoretical yields of 42-62% with a reaction time that endures about 15 mins to 2 hours, all depending on the moisture content of the product feed.

In 2002, Rumerman and al. [13] developed the Twin-retort carbonization process in Netherland, the system produces charcoal at a rate of 900 tons per year, it has an efficiency of about 33% with carbon content of 92% and the emissions were reduced by at least a factor of two. In 2005, the UK, Syred and Al. [14] introduced the Charcoal Heat and Power (Charcoal, Heat and Power) process, which develops a method for producing clean efficient charcoal under pressurized conditions and uses the product gas from the carbonization process in order to drive a small gas turbine to produce both heat and power. This process showed a yield of 38%.

In 2009, J.C Adam [15], built the ICPS (Improved Charcoal Production System) unit, which resulted in a yield of 30% to 42% and hence reduced the emissions to the atmosphere by up to 75%. The ICPS works in two different phases. During the first phase, the ICPS works typically like a traditional kiln; however, waste wood is burned in a separate fire box in order to dry the wood. During the second phase, the harmful volatiles are burned in a hot fire chamber and thus making all resulting emissions cleaner, and hence all volatiles are reduced. The heat that is gained by flaring the wood gazes is used and recycled and this is done for the purpose of accelerating the carbonization process. Unlike traditional methods, the ICPS is able to complete a carbonization process within 12 hours.

Also, in 2009, Elyounssi et al. [16] introduced the two-step pyrolysis process. The first phase concern was about hemicelluloses and cellulose decomposition. During that phase, char formation was advanced by low temperatures. At the end of that phase, the fixed carbon yield was maximum. The maximum value attained was as great as that obtained under high-pressure pyrolysis and approached the theoretical value. During the second phase of the low temperature isothermal pyrolysis, the fixed-carbon yield decreases, what proves the loss of the already existing carbon. However, this immediate rise in temperature at the end of the first phase helped preserving the value of the fixed-carbon yield at a maximum. This process contributed in the increase of the charcoal quality without excessively decreasing charcoal yield.

CHAPTER III

CHARCOAL RETORT DESIGN

A. CFD modelling

1. Modelling

a. <u>Literature review</u>

CFD or Computational Fluid Dynamics are carried out in order to appraise the applicability and efficiency of the generated retort design.

Many researchers have been using different Computational Fluid Dynamics software to model combustion units and to evaluate their performance and thus to improve their design and its operation, benefiting from the strong built-in capacities that the CFD software packages usually have.

In 2005, Syred et al. [14] developed the ChaP process (Charcoal, Heat and Power) to produce clean efficient charcoal under pressurized conditions, in this process they used the product gas from the carbonization process to drive a small gas turbine to produce heat and power. In order to test the applicability of their design, they used the Fluent 6 to model the system and to extract the temperature profile across the combustor.

Later in 2014, Hiroki Homma,from “National Institute of Technology, Matsue College” in Japan, and Hiroomi Homma and Muhammad Idris from “ University of North Sumatera” in Indonesia worked on achieving a numerical analysis of wood pyrolysis in pre-vacuum chamber [17]. Using Ansys meshing tool, they generated a 2D mesh for the cross section of their proposed furnace and pre-vacuum chamber. Two-step general reaction model is proposed for the numerical analysis, the first stage is volatile and char formation from wood following carbonization, and the second state is decomposition of the volatile to five species including vapor of tar. After identifying the chemical reaction formula of each stage, they used the Ansys Fluent 12.0 to study the heat transfer and the chemical reactions taking place inside the pre-vacuum chamber during the pyrolysis process.

Another combustion simulation was achieved in 2015. Smail Kalla et al. simulated the combustion in a natural draft residential wood log stove [18] using Ansys Fluent 14.0. To solve the aero-thermodynamic equations inside the stove they used the RANS approach, and the chemical reaction for combustion was modeled using species transport model and rate of species production formulated as the Eddy Dissipation Concept. In order to ensure the closure of the Navier Stokes equations the k-ε turbulence model was adopted. Also, they used Ansys meshing tool to mesh the studied stove design.

Also in 2015, Edwin Luwaya [19] from university of Zambia used the PHOENICS CFD software to simulate the major factors influencing the conversion efficiency in an earth charcoal production kiln, trying to improve this efficiency by applying a scientific approach using a numerical method. Luwawa concluded that several factors have influence on the conversion efficiency of wood pyrolysis process inside an earth kiln such as the moisture content of wood, the diameter of the wood logs, the dimensions of the kiln, and the wood arrangement type inside the kiln.

Recently in 2017, Danielle R. S. Guerra et al. [20] used the ANSYS Fluent 14.0 to model the combustion process in their horizontal cyclonic combustion chamber burning biomass powder. The simulation aimed at obtaining the temperature and velocity profiles as well as the species mass fraction distribution, using the species transport model as the reaction model, the Euler-LaGrange model(ELM) approach to solve the biphasic reactive flow. They also used the k-ε RNG turbulence model to predict the cyclonic behavior of the gaseous flow. The computational mesh was done using the Ansys meshing tool.

although there is not so much literature on CFD simulations for charcoal pyrolysis retorts, but the use of Ansys Fluent package to simulate and model the combustion chambers in different applications is of a great significance concerning the reliability of this CFD software, and that's what prompted us to use it to simulate and model our proposed design.

b. <u>3D simulation attempt</u>

A preliminary design of the retort was modelled using Ansys Workbench - Fluent 14.0. The main purpose of the CFD simulation 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

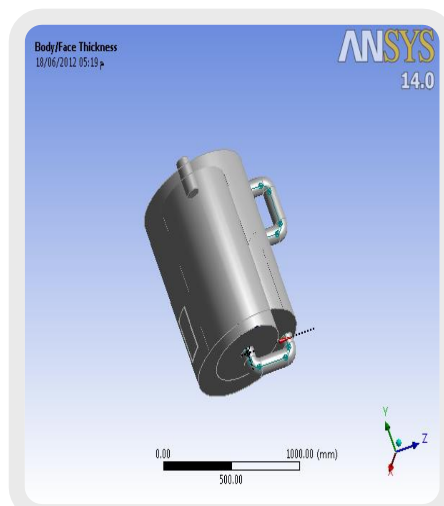

Figure 12: the retort design used in the 3D simulation

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 12 shows the design used in the simulation. ANSYS meshing tool was used to mesh the model, but the resulting number of cells and nodes was too large (see Figure 13) thus the number of iterations needed for the simulation to converge was extremely so large and so much time consuming. The preliminary results for the temperature and velocity contours (see Figure 14) were not satisfying, therefore, we decided to settle for a 2D simulation.

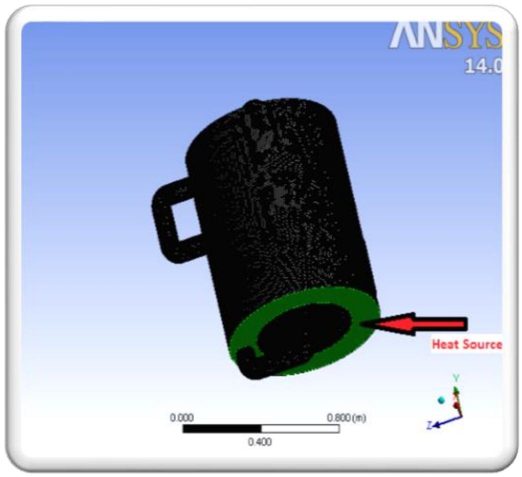

Figure 13: meshing of the design showing the large number of cells and nodes

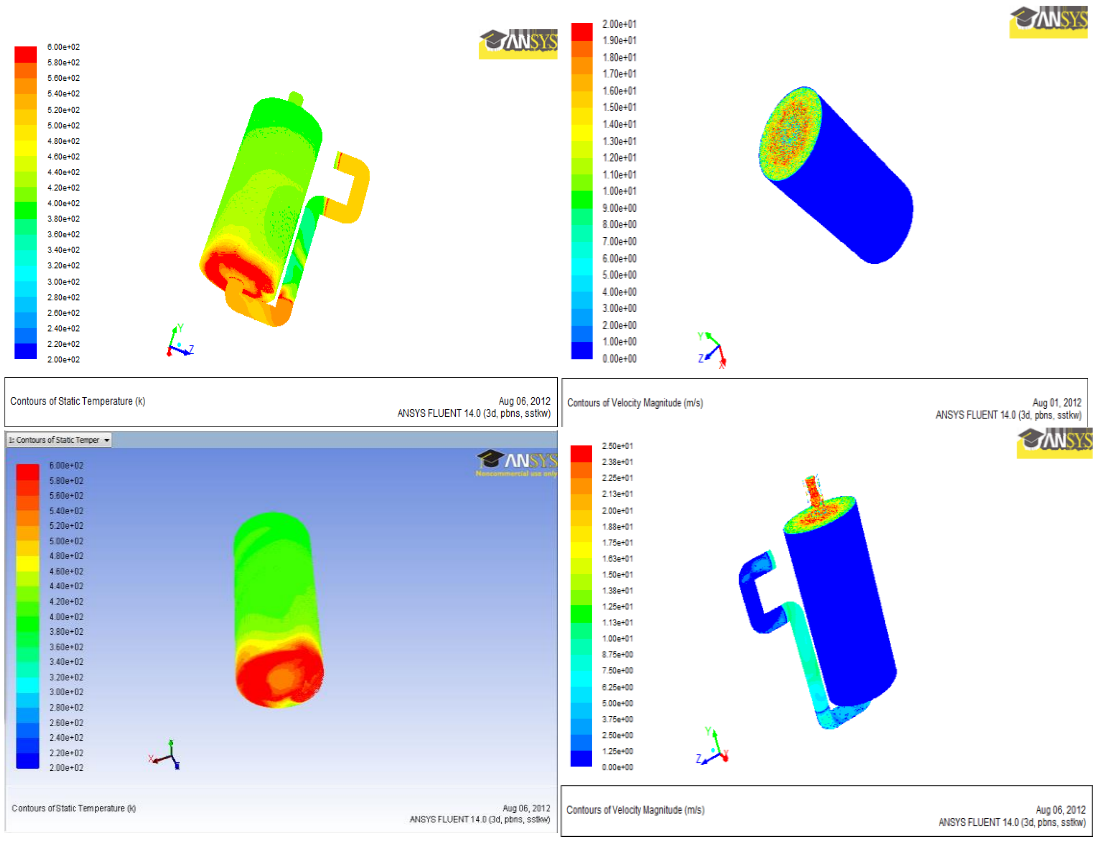

Figure 14: 3D simulation preliminary temperature and velocity contours

c. <u>2D simulation</u>

In 2D simulation, using ANSYS Fluent package 17.2, 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 as 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 can 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. 15).

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.

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.

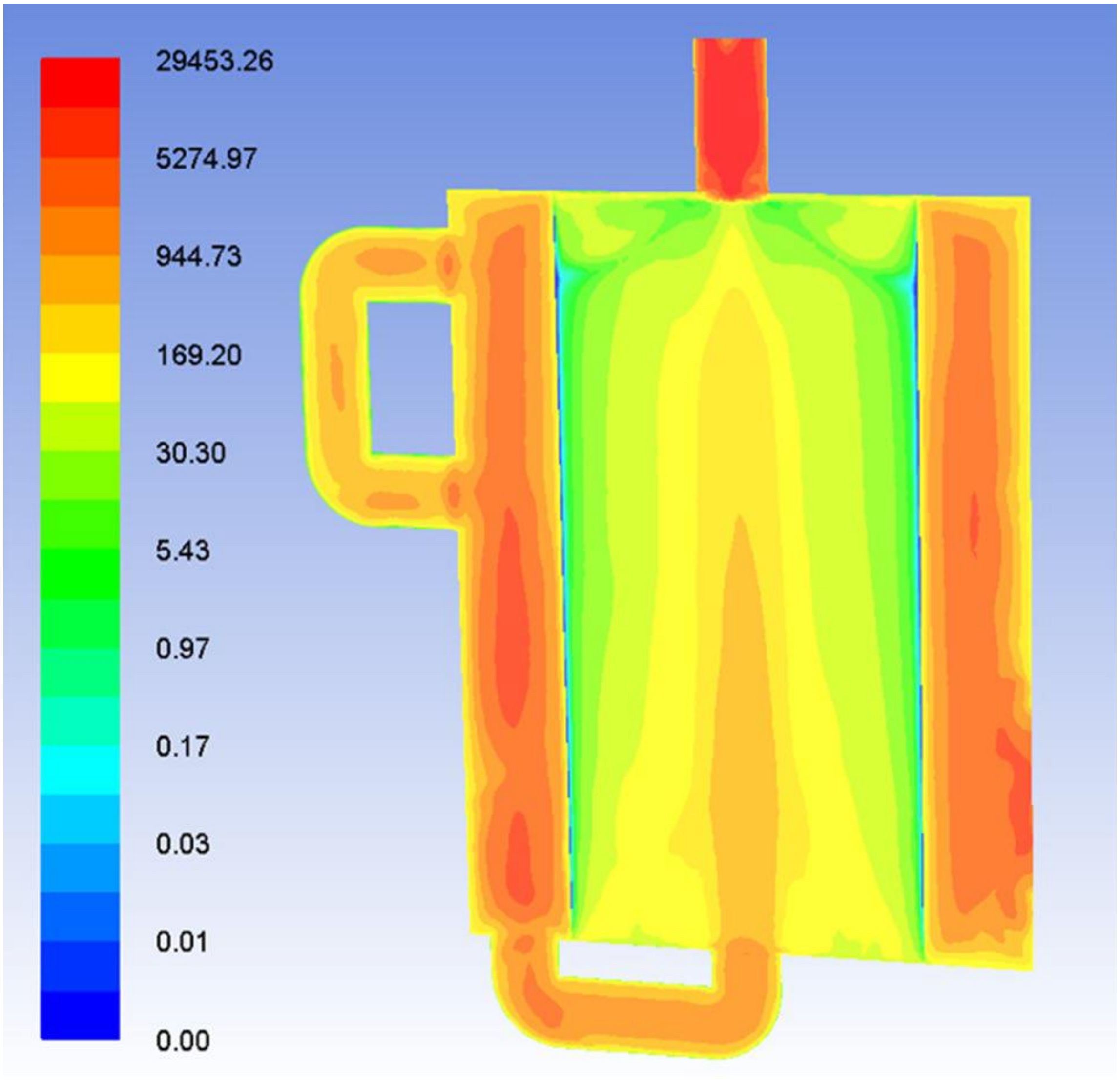

Figure 15: Contours of Reynolds number (log scale)

2. Simulation results

To assess the applicability and efficiency of the proposed retort design, the CFD simulation was carried out. 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. 16, 18), which was a key condition to guarantee the operation of the proposed design. Figure 16a shows that the velocity in the flue-gas recycle line ranges between 0.006 and 0.03 m/s while Fig. 16b 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. 16b) at a velocity of 4 m/s. In addition, the streamlines in Fig. 18a,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. 17). However, higher 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. 19, valves V1 and V2). Furthermore, the pipe of the flue-gas recycle line that introduces the combustion gases into the carbonizer (Fig. 19, 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.

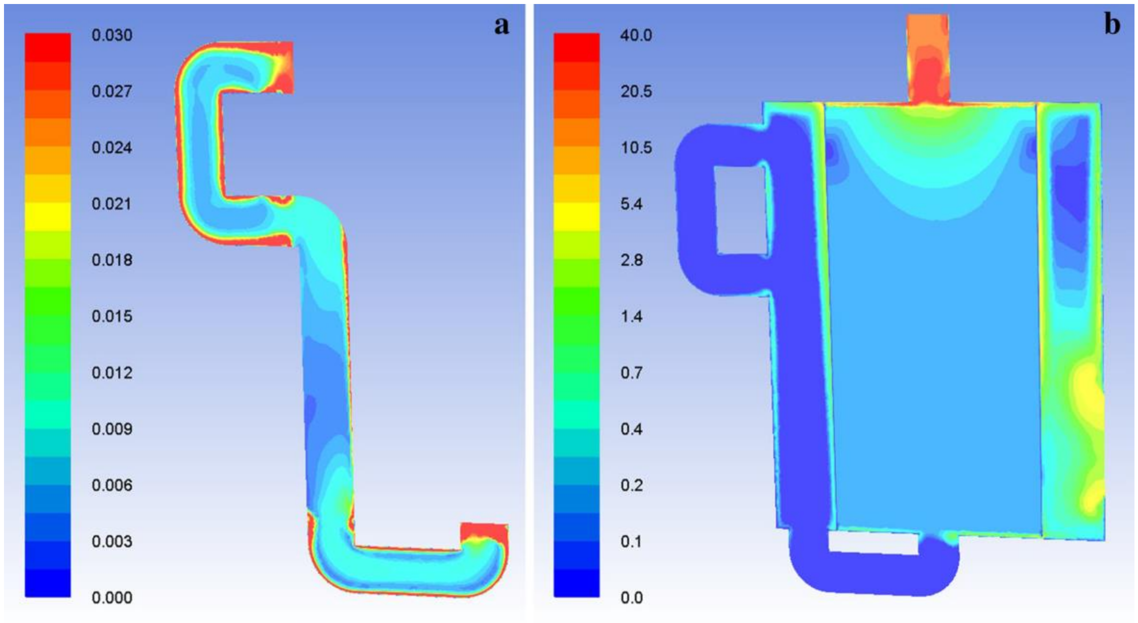

Figure 16: Velocity contours (m/s) (log scale). a) In flue-gas recycle line, b) in combustor and carbonizer

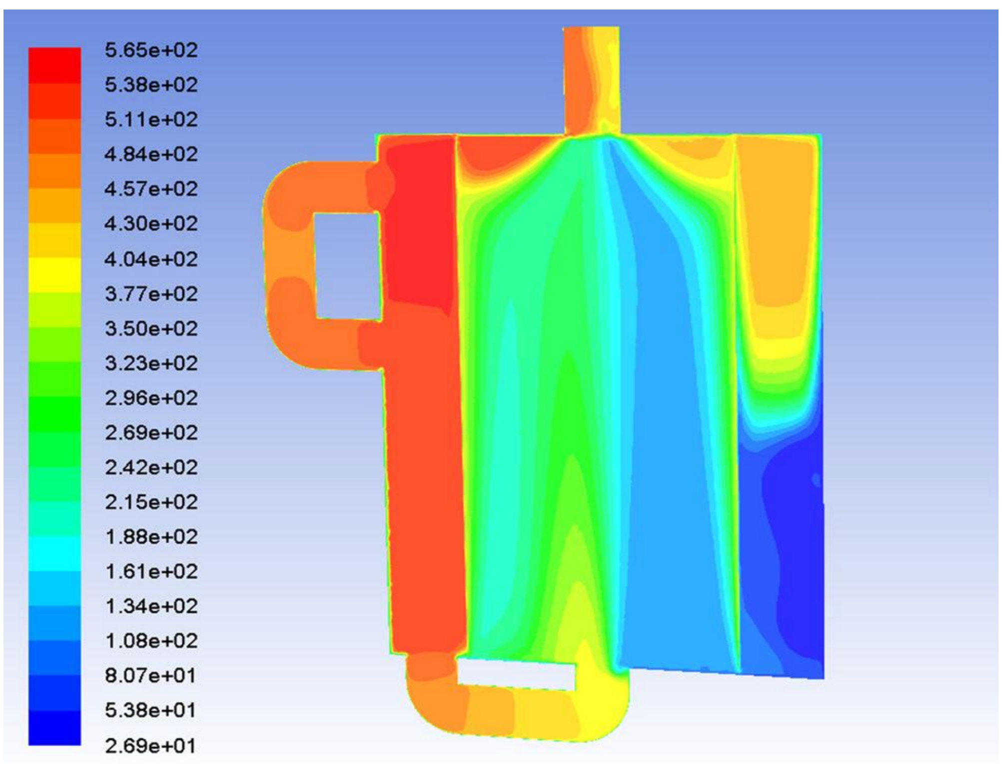

Figure 17: Contours of static temperature (°C)

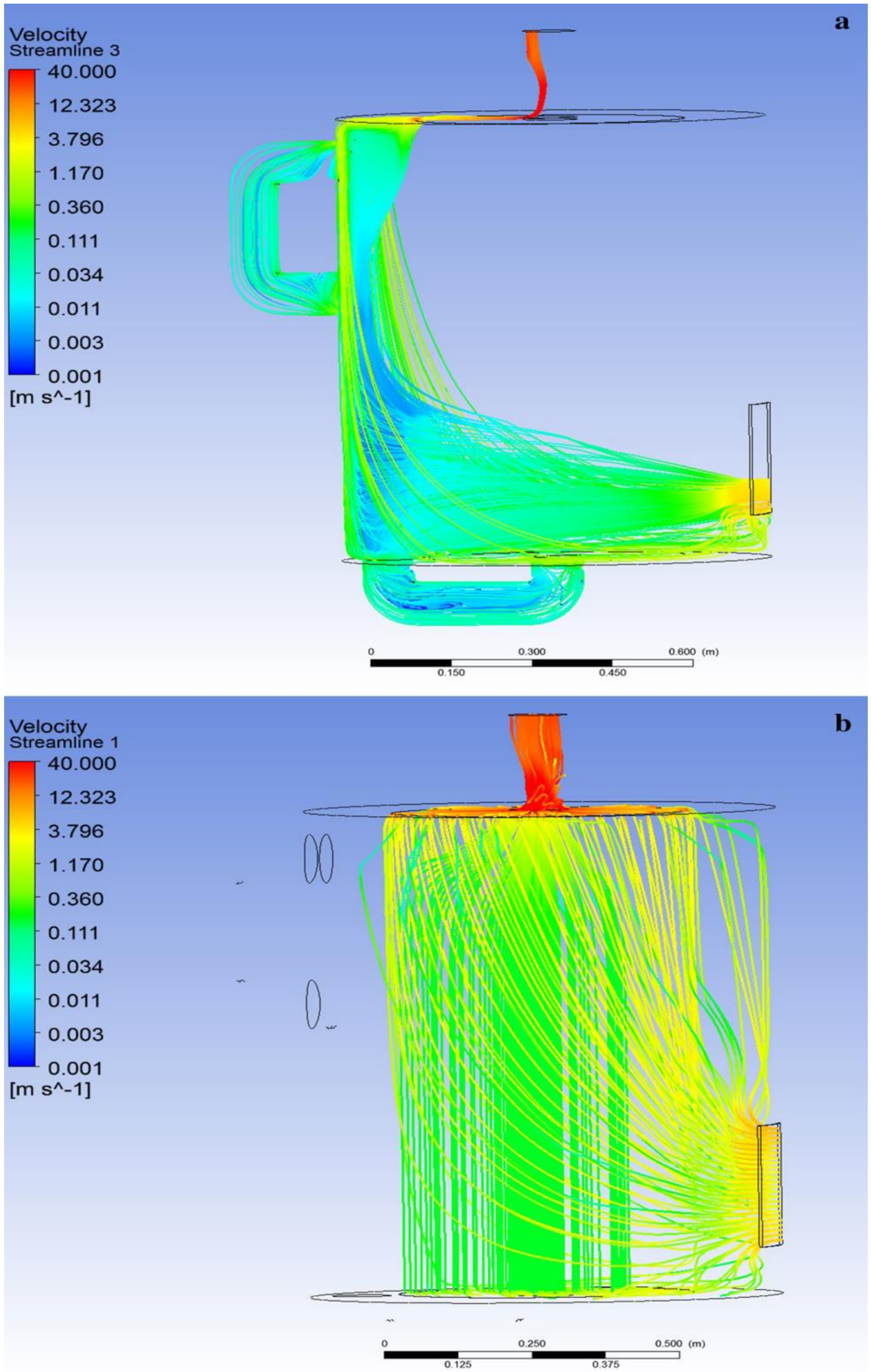

Figure 18: Plot of streamlines (m/s) (log scale). a) inside flue gas recycle line and combustion zone, b) inside carbonizer and combustion zone

B. Mechanical design

The final 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 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 (Figure 19) are used to monitor the temperature in the different parts of the retort, and to ensure 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

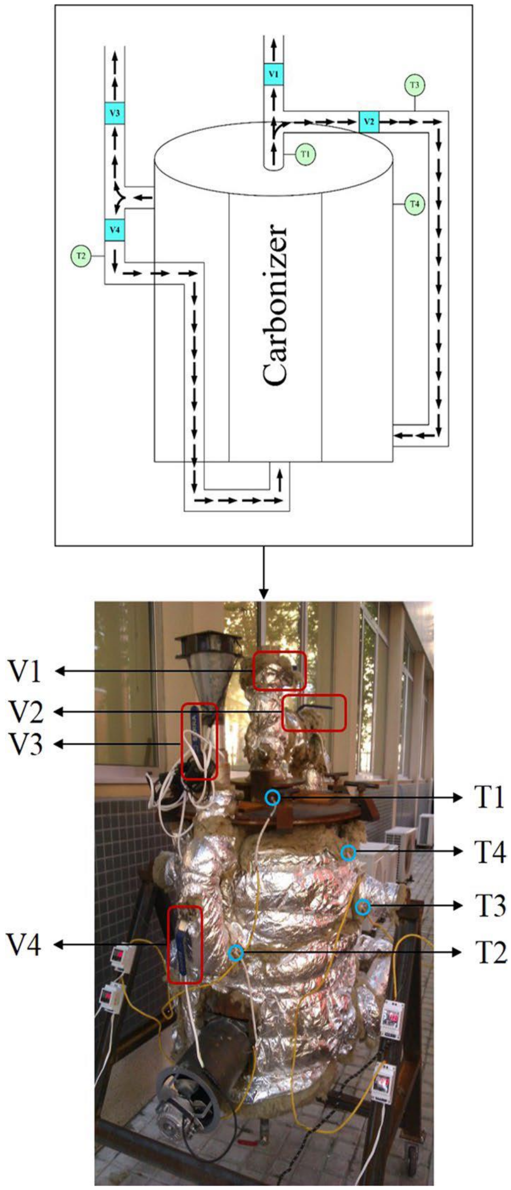

Figure 19: Valves and thermocouples locations in the built design.

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. 19 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 to minimize heat losses and decrease energy consumption during the carbonization process. (See Figs. 19, 20, 21 for design annotations of valves, thermocouples and insulation, and the interior of the design).

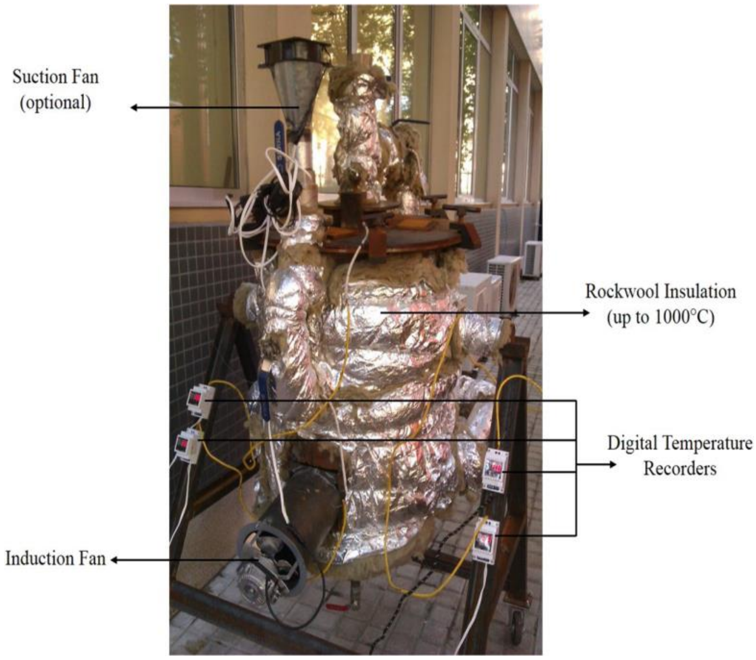

Figure 22:The designed retort showing induction and suction Fans, Rockwool insulation and four digital temperature recorders.

Figure 25: Different components of the built prototype

CHAPTER IV

EXPERIMENTAL WORK AND RESULTS

A. Experimental work

The system was successfully tested after implementing the modifications in the design. Similar 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 around 5 kg oak wood with different water contents measured according to ASTM D 2016-74 were used as raw materials. The produced charcoal samples were taken after achieving each experiment and analyzed according to ASTM D 1762-84 standards to specify the composition of each charcoal sample.

Along the procedure of our work, three experiments were conducted.

1. First experiment

In the first experiment, 5788g of wood was used as a raw material in the process, to be transformed into charcoal. Its water content is 12.8%. Its dry weight in grams is 5046. After the experiment was almost done, after waiting for exactly 1h 15 min, the proceeded charcoal weight is 2317.The yield on wet basis is 40% and the yield on dry basis is 46%.

2. Second experiment

In the second experiment, 4792g of wood was used as a raw material in the second process, to be transformed into charcoal. Its water content is 8.3%. Its dry weight in grams is 4394. Two hours and 15 minutes later, the generated charcoal weight is 1811g. The yield on wet basis is 37.8% and the yield on dry basis is 41.2%.

3. Third experiment

In the third experiment, 5420g of wood was used as a raw material in the third procedure, to be transformed into charcoal. Its moisture content is 8.3% and its dry weight in grams is 4967.Two hours and fifty minutes later, the generated charcoal weight is 1840g.The yield on wet basis is 34% and the yield on dry basis is 37%.

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 1%

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

4. Process Control and Results

The temperature inside the carbonizer peaked in 20 mins to 900 °C (at 75 min

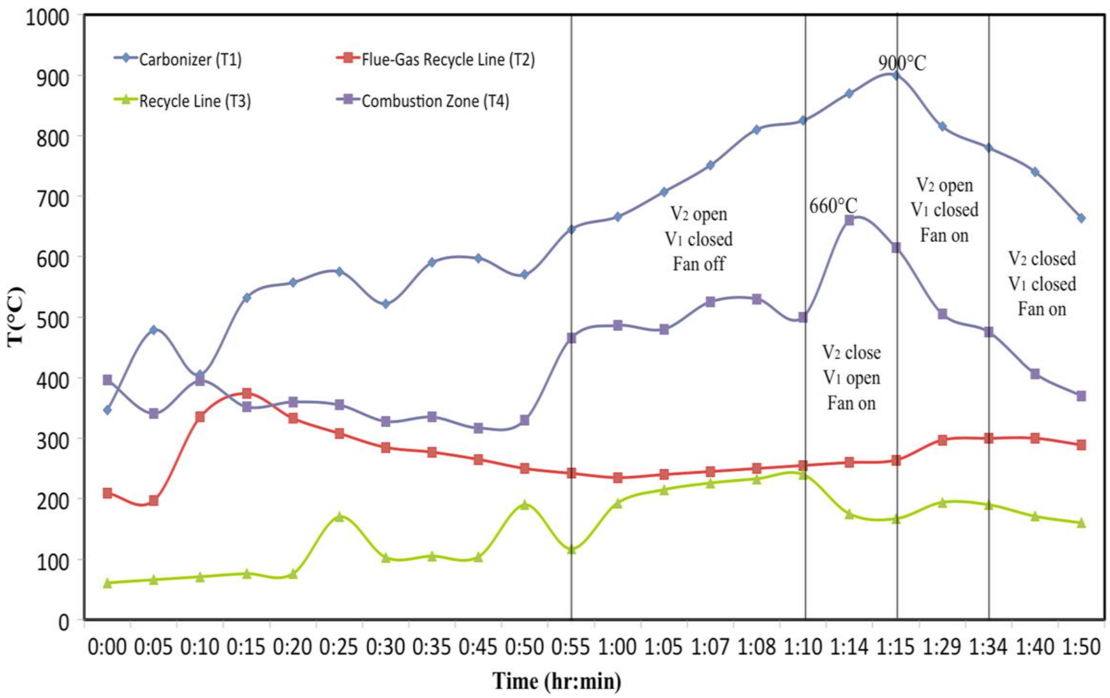

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Figure 26: Temperature profiles recorded by the thermocouples and valve operations performed

t

= 0) (Fig. 22). 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 22 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 (First experiment) showed the highest charcoal yield on dry basis (Y_d) of 46% with carbon content of 73% achieved in 1 h and 15 mins, while the process operated at 650 °C (Second Experiment) showed a lower charcoal yield on dry basis (Y_d) of 41% with a higher carbon content of 77,6% achieved in 2 h and 15 mins. However, when operating the retort at 900 °C (Third experiment), a lower yield (37%) and a higher carbon content (87%) and operation time (2 h and 50 mins) were observed. Therefore, increasing the process temperature produced more volatiles resulting in a yield decrease while increasing the carbon content in the product.

Table 2: Charcoal product analysis measured according to ASTM D1762-84 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

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

A. Results Discussion

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 table 1 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 consider 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 reactor design, operating temperature and heating rate, and type of feedstock [21–23]. Table 3 below compares our design with published results showing in each case the production method used and the charcoal yield achieved.

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

Production method	Yield (%)	References
Gas generation using the "inverted downdraft gasifier" principle, in one mode of operation	20–25	Reed et al. [11]
Pyrolysis is accomplished at elevated pressures in a stagnant gas environment	42–62	Antal et al. [12]
Twin-retort carbonization process	33	Reumerman et al. [13]
CHaP (charcoal, heat and power) process	38	Syred et al. [14]
ICPS (improved charcoal production system) unit	30–42	Adam et al. [15]
Two-step pyrolysis process	60	Elyounssi et al. [16]
Partial combustion in charcoal kilns	40	Saravanakumar et al. [24]
Biomass carbonization system using microwave heating	31	Payakkawan et al. [25]
Two-step process slow high temperature pyrolysis	20–28	Solar et al. [26]
Two-concentric cylindrical retort	46	Suggested design

B. Recommendations

Based on the proposed design, future work can focus on optimizing this design to be more energy efficient and to integrate more components, so the retort becomes able to recover all types of energy produced during the pyrolysis process, therefore we recommend the following:

- Utilize the gases emitted as a source of energy and use them to generate electricity in a gas or steam turbine.
- Integrate a storage tank to the suggested design to store the emitted gazes from the pyrolysis process and perform chemical decomposition to get simpler chemical products.
- Optimize the suggested design by studying the heat transfer inside the retort and re-dimension it to get the maximum heat efficiency.

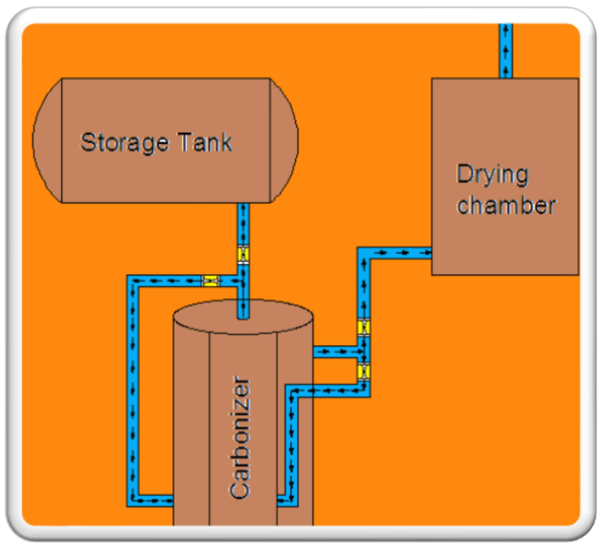

Figure 29: llustration of possible future work

Figure 30: llustration of possible future work

- Improve the suggested design by automating the valves control system, so to achieve a better performance and to decrease the number of labors needed to operate the retort.

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