Numerical Simulation of Different Configurations for a Combined Gasification/Carbonization Reactors

Mahmoud Amer, Ibrahim El-Sharkawy, Shinichi Ookawara, Ahmed Elwardany

Abstract—Gasification and carbonization are two of the most common ways for biomass utilization. Both processes are using part of the waste to be accomplished, either by incomplete combustion or for heating for both gasification and carbonization, respectively. The focus of this paper is to minimize the part of the waste that is used for heating biomass for gasification and carbonization. This will occur by combining both gasifiers and carbonization reactors in a single unit to utilize the heat in the product biogas to heating up the wastes in the carbonization reactors. Three different designs are proposed for the combined gasification/carbonization (CGC) reactor. These include a parallel combination of two gasifiers and carbonized syngas, carbonizer and combustion chamber, and one gasifier, carbonizer, and combustion chamber. They are tested numerically using ANSYS Fluent Computational Fluid Dynamics to ensure homogeneity of temperature distribution inside the carbonization part of the CGC reactor. 2D simulations are performed for the three cases after performing both mesh-size and time-step independent solutions. The carbonization part is common among the three different cases, and the difference among them is how this carbonization reactor is heated. The simulation results showed that the first design could provide only partial homogeneous temperature distribution, not across the whole reactor. This means that the produced carbonized biomass will be reduced as it will only fill a specified height of the reactor. To keep the carbonized product production high, a series combination is proposed. This series configuration resulted in a uniform temperature distribution across the whole reactor as it has only one source for heat with no temperature distribution on any surface of the carbonization section. The simulations provided a satisfactory result that either the first parallel combination of gasifier and carbonization reactor could be used with a reduced carbonized amount or a series configuration to keep the production rate high.

Keywords—Numerical simulation, carbonization, gasification, reactor, biomass.

I. INTRODUCTION

THE depletion and rising cost of fossil fuels along with the rising greenhouse effect urged researchers to look for a proper alternative for them. Thus, the increasing interest in renewable energy resources took a larger place in today's research. Renewable energy is defined as the energy obtained

Mahmoud Amer is with the Fuels and Combustion Engines Laboratory, Energy Resources Engineering department, Egypt-Japan University of Science and Technology (E-JUST) 21934, Egypt (e-mail: mahmoud.omar@ejust.edu.eg).

Ibrahim El-Sharkawy is with Energy Resources Engineering Department, E-JUST 21934, Egypt (e-mail: ibrahim.elsharkawy@ejust.edu.eg).

Shinichi Ookawara is with the Department of Chemical Science and Eng., Tokyo Institute of Technology, Tokyo 152-8552, Japan (e-mail: sokawara@chemeng.titech.ac.jp).

Ahmed Elwardany is with the Fuels and Combustion Engines Laboratory, Energy Resources Engineering Department, E-JUST 21934, Egypt (corresponding author, phone: +201204418107 e-mail: ahmed.elwardany@ejust.edu.eg).

from naturally repetitive and persistent flows of energy occurring in the local environment [3]. This can be achieved by finding alternative fuels that can replace the fossil fuels. These alternatives can be produced from biomass because they are an alternative renewable source of carbon. Biomass is a term for organic waste that stems from plants and produced by photosynthesis making them all green energy resources. During their formation, biomasses already used the exact same amount of carbon dioxide they will later emit as exhaust, so they are usually referred to as a carbon neutral fuel when it is burnt [4]-[6].

Waste biomass encompasses a wide range of materials and their availability is advantageous. The wastes usually have a trivial value and could be considered as a pollutant to environment due to their wrongful disposal methods. There exist many sources of waste biomass either from agriculture or industrial sectors as waste from agricultural processes or frozen vegetables/fruits factories, respectively. The usage of these different kinds of biomasses has positive economic and environmental impacts and can be called a truly renewable source. That's because they can be converted from waste into a real source of income. There exist numerous pathways to upgrade the biomass into biofuel either by thermo-chemical or bio-chemical methods [7], [8]. In the current work, a focus will be put on thermo-chemical conversion.

Biomass thermo-chemical conversion is performed by heat application to start the decomposition of organic materials by cracking the hydro-carbonaceous bonds to transform it into a richer form of energy. Thermo-chemical conversion processes include combustion, pyrolysis, carbonization, co-firing, gasification, and liquefaction [9]. Pyrolysis is considered as the starting point of all thermo-chemical conversion technologies. It involves all chemical reactions to form solid "char", liquid "bio-oil", and gas "biogas" carried out under oxygen-free or oxygen-limiting conditions. The gases and the bio-oil are from the volatile fraction of biomass, while the char is mostly the fixed carbon component [10]. Specifically, gasification and carbonization only are the main concern of the current project.

Gasification is the process of converting biomass to a gaseous fuel by heating in a partially oxidative environment such as air, oxygen, or steam. While combustion requires complete oxidation to fully burn the biomass, gasification converts the intrinsic chemical energy of the carbon in the biomass into a combustible gas to be used elsewhere. The gasification process adds hydrogen to and strips carbon away from the feedstock to produce gases with higher hydrogen-to carbon (H/C) ratio. The produced biogas can be standardized

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:14, No:9, 2020

in its quality and is easier to be use compared to the raw biomass [11]. There exist many types of gasifiers and each type has a different application. These types are grouped into mainly three categories namely, fixed, fluidized and entrained bed gasifiers [12]. Each one of them is subcategorized into many configurations. A comparison among the three categories is shown in Table I [1]. The simplest and most used category is the fixed bed type. Fixed bed gasifiers have 3 subcategories; updraft, downdraft and crossdraft [1], [2] which are compared among each other in Table II.

TABLE I
COMPARISON AMONG THE GASIFIERS' MAIN CATEGORIES [1]

Parameter	Fixed Bed	Fluidized Bed	Entrained Bed
Biomass feed size (mm)	<51	<6	<0.15
Tolerance for fine particles	Limited	Good	Excellent
Tolerance for coarse particles	Very good	Good	Poor
Syngas exit temperature (°C)	450-650	800-1000	>1260
Oxidant requirement	Low	Medium	High
Resulting Ash	Dry	Dry	Slagging
Capacity	Small	Medium	Large

TABLE II
SELECTION CRITERIA OF THE FIXED BED GASIFIER TYPE [1], [2]

Parameter	Updraft	Downdraft	Crossdraft
Moisture content (Max) (%)	60	25	20
Ash content (Max) (%)	25	6	0.5
Feed size (mm)	5-100	20-100	5-20
Syngas exit temperature (°C)	200-400	700	1250
Tar content	High	Low	Extremely low
Syngas LHV (Mj/m3)	5-6	4.5-5	4-4.5
Manufacturing complexity	Simple	Complex	Complex

Carbonization is the oldest known thermo-chemical process that allowed humans to convert wood into charcoal, which is the first biofuel that has been used by humans to step out of the stone-age by refining ores into metals. The carbonization process occurs slowly heating the biomass to high temperatures exceeding 400 °C and for several hours. The products from this process are charcoal when it is used as fuel, biochar when used as fertilizer or soil amendments, biocoke for metal extraction and finally activated carbon when regular charcoal is upgraded for adsorption and purification purposes.

The combination between carbonization and gasification systems has been discussed in the literature. As far as the authors know, all systems start with carbonization to produce a better feed for the gasification systems because it is a well-known fact that char in general is a better feed for gasifiers than wood or raw biomass which increases the gasifier's efficiency [1], [13]. This combination started as early as 1987 when Kasaoka et al. [14] studied the effect of coal carbonization on gasification performance. Ichikawa et al. [15] got a patent for a carbonization, gasification combined system. In their system, the biomass is first carbonized, and the produced char and pyrolysis gas fed to a high temperature gasifier. The gasifier products are fed into a power generation system where its high temperature exhaust heats the carbonization reactor to reduce the kerosene or heavy oil used in the carbonization stage. Many other similar systems

employed regular carbonization [16]-[19] and hydrothermal carbonization [20]-[24]. The heat source for the carbonization process was nOt discussed extensively in the literature. However, when it was mentioned, fossil fuels or burning raw biomass to supply the heat were utilized.
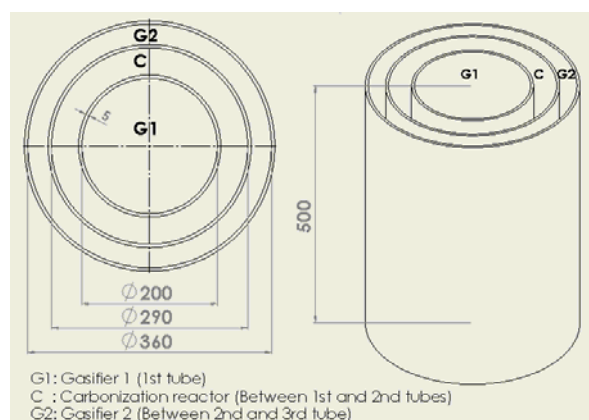
In the proposed system, the process is inverted to overcome using any fossil fuel or even burning raw biomass which is inefficient. The biomass will be gasified first to generate enough syngas and heat to carbonize the biomass. This carbonized biomass can either be used as a fuel or fed into another gasifier to produce a higher quality syngas. This is to form the CGC reactor.
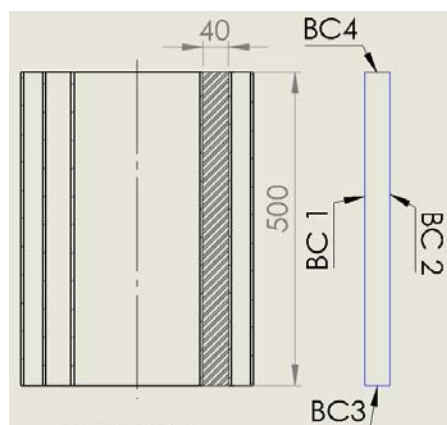
II. METHODOLOGY

The current study starts with initially developing three different 2-D configurations for the CGC reactor to numerically assess the temperature distribution and uniformity across the carbonization reactor. Then a conclusion is made based on these results to select the best configuration.

A. Proposed CGC Reactor Designs

The proposed design is based on the idea that the reactor is composed of three concentric tubes as shown in Fig. 1 (a). The three volumes between the tubes represent different reaction zones. These zones are G1 which represents the 1st inner gasifier, C which represents the carbonization reactor and G2 which represents the outer gasifier. The dimensions shown in Fig. 1 (a) are taken on the account that the three spaces would have the same volume and subsequently the same mass. The volume is approximately 15.5 litres per space which can be easily converted into mass if the biomass's density is known. The common thing among the 3 designs is that the carbonization reactor is always in the middle. The 1st and 3rd spaces change according to the different designs. Three different designs for the CGC reactor are suggested as shown in Fig. 2. Numerical evaluation of these designs is performed to assure homogeneity of temperature distribution inside the carbonization reactor. The evaluation decides whether one of these 3 designs is the best or a completely different fourth design would be required.


G1: Gasifier 1 (1st tube)
C : Carbonization reactor (Between 1st and 2nd tubes)
G2: Gasifier 2 (Between 2nd and 3rd tube)

(a)

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
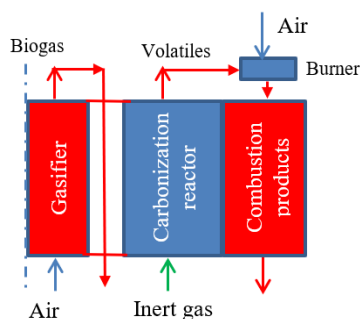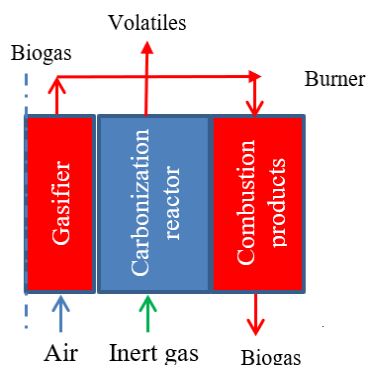Vol:14, No:9, 2020

(b)

Fig. 1 (a) Initially Proposed CGC reactor, (b) cross sectional view indicating the simulation hashed area with boundary conditions
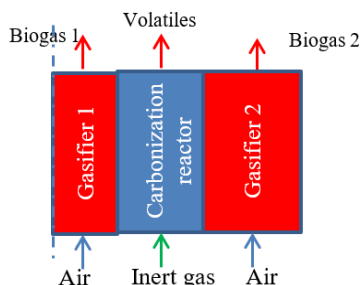
(a)

(b)

(c)

Fig. 2 Half centreline sectional view for the 3 proposed designs

Fig. 2 (a) represents the first design where the carbonization reactor (C) is sandwiched between two gasifiers (G1 and G2). The two gasifiers are supposed to be of the same type. For the sake of the simulation, updraft gasifier would be taken into consideration wherever a gasifier is proposed. Fig. 2 (b) represents the second design which incorporates only 1 gasifier. The design is slightly modified with a 4th tube to create an anulus space between G1 and C. In this space the biogas that resulted from G1 will flow to heat the carbonization reactor from the inner side. In G2 there will be combustion which will be from burning the volatiles that are released from the carbonization reactor. Fig. 2 (c) represents the third design where the carbonization reactor (C) is heated from the gasifier (G1) from the left and in G2 there will be combustion for the biogas that exited from (G1).

B. Numerical Setup

Ansys Fluent CFD 17.2 was used to perform the numerical simulations. The developed model is transient and uses heat conduction model via the application of the energy equation. Parallel computing is implemented using a Dell Precision T7500 workstation with an Intel Xeon® processor of 3.75GH, 48-core, and 64-MB installed memory. The numerical solution convergence was tested at each time step, with the convergence measure of 10-6 for all results. The solver is based on the transient pressure-based Navier-Stokes solution algorithm and the absolute velocity formulation which are the default settings.

C. Initial and Boundary Conditions

Initially, the whole system is assumed to be at the ambient temperature of 300 K. The main purpose of running simulation is to find out which design would result in the best temperature distribution across the carbonization section. As this design results in completely symmetrical design around its centreline, only simplified 2D simulation can be performed. The 2D design can be as simple as rectangle resembling the carbonization reactor which is surrounded by boundary conditions (BC) from its four sides as shown in Fig. 2 (b). These BC are specified as wall temperature inputs for each case shown in Fig. 1 as mentioned in Fig. 2 (b).

TABLE III
BC FOR THE 3 PROPOSED CASES SHOWN IN FIG. 1

	BC 1	BC 2	BC 3	BC 4
Case (a)	Gasifier temperature profile	Gasifier temperature profile	Insulated	Insulated
Case (b)	Biogas exit temperature	Combustion temperature	Insulated	Insulated
Case (c)	Gasifier temperature profile	Combustion temperature	Insulated	Insulated

D. Numerical Method

The model characteristics are carefully studied based on the mesh and time step independent solutions to reach the best accuracy with a reasonable time based on the dimensions shown in Fig. 2 (b). The area weighted average temperature of the carbonization reactor was chosen as a criterion for optimal design selection. The surface weighted average temperature which resembles the steady state uniform temperature will be

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:14, No:9, 2020

taken as 98% of the wall's temperature.

The materials used in the simulation are stainless steel for the boundaries of the reaction area and wood for the reaction area. Although wood is solid in this case and biomass has voids, but these conditions can provide appropriate preliminary results. For both the mesh and time independent solutions, BC1 and BC2 are set to 600 K, biomass initial temperature = 300 K, and the area weighted average temperature = 590 K. The calculations were terminated when the average temperature of the reactor reaches the set value of 590 K. This ensures a uniform temperature distribution across the carbonization area.
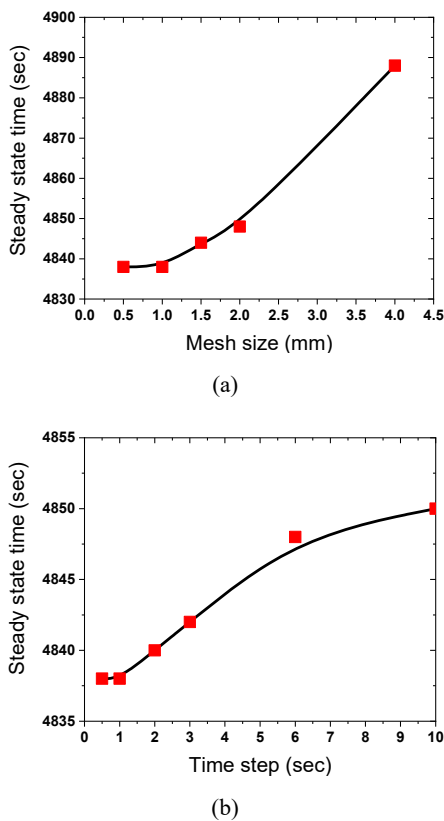

(a)

(b)

Fig. 3 Mesh independent solution (a) and the time step independent solution (b)

For the mesh size independent solution, a simulation time step is taken constant value of 1 second, and a coarse mesh size is taken first to be 4 mm. The simulation is run, and the steady state time is recorded. The mesh size is then reduced to finer values of 2, 1.5,1 and 0.5 mm and each time the steady state time is recorded. The relation between time steady state time and mesh size is recorded and plotted in Fig. 3 (a). It can be clearly seen from Fig. 3 (a) that the time started to be constant at a mesh sizes of less than 1 mm. So, a 1 mm mesh size is used in all the following cases. In the time step independent solution, the mesh size is taken 1 mm from the mesh independent solution. An initial large time step is initially taken to be 10 seconds, then reduced to smaller values of 6, 3, 2, 1 and 0.5 seconds. Each time the steady state time is recorded against the simulation time step and this relation is

plotted in Fig. 3 (b). Fig. 3 (b) clearly shows that the simulation time became the same at time steps of 1 sec and less. So, a simulation time step will be taken 1 sec. So, for the 3 cases illustrated in Table II, the mesh size will be taken 1 mm and the time step will be taken 1 second.

III. RESULTS AND DISCUSSION

The simulation will run for 18000 time-steps which equals 5 hours in the 3 cases to ensure that steady state is obtained, and the final temperature distribution contour across the carbonization reactor will be plotted and compared among the three cases. The following conditions are considered for the next simulations:
- Gasifier temperature profile is taken for updraft gasifier which has a temperature profile shown in Fig. 4 [11].
- Biogas exit temperature: taken 500 K from Fig. 4 [11].
- Combustion temperature: assumed 800 K.
- Carbonization reactor's biomass initial temperature: assumed 300 K.

The results from running the 3 cases are shown in Fig. 5. Fig. 5 shows that for the 3 cases, the temperature distribution is not uniform across the carbonization reactor. This concludes that these designs will not result in a uniform temperature distribution along the whole carbonization reactor which results in a non-homogeneous product. It could be seen from Fig. 5 (a) that the carbonization reactor has a semi-homogeneous temperature distribution. This means that the first design could be used but only when divided into vertical sections which will reduce the produced biomass. This highlights that the parallel combination of gasifier and carbonization reactor may not be efficient. Hence, a series combination could be proposed to ensure homogeneous heating.

The conclusion from the above results is that in order to have a uniform temperature distribution across the carbonization reactor, there cannot be any temperature fluctuation across the same surface or even between the two surfaces of the carbonization reactor. So, the whole carbonization reactor must be subjected to the same temperature from all sides. This means that only one source of constant temperature must be used to carbonize the biomass or two sources with the same constant temperature.
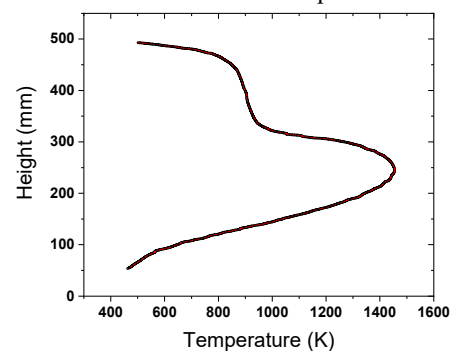

Fig. 4 Updraft gasifier temperature profile [11]

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
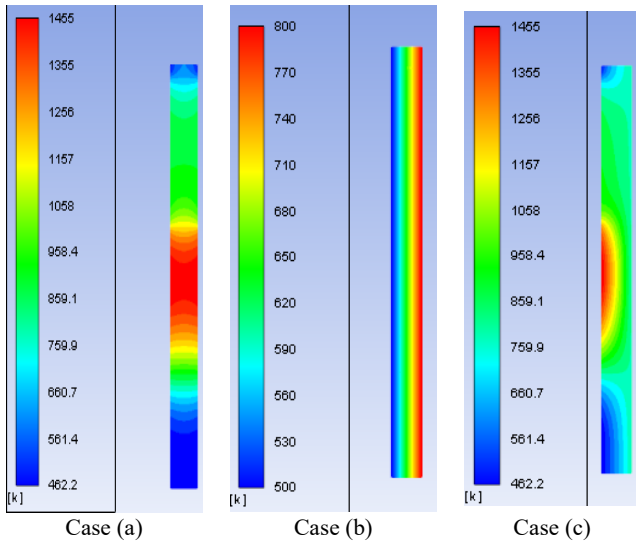Vol:14, No:9, 2020

Fig. 5 Steady state temperature distribution across the carbonization reactor for the 3 proposed cases in Table III

The proposed design is to have only a single gasifier to supply the heat to the carbonization reactor. The output syngas from this gasifier will be used to supply the heat required to perform the torrefaction or the carbonization processes. If the temperature of the syngas is low, the syngas will be burnt to increase the temperature. So, the design will comprise of the gasifier and a heat exchanger. The heat exchanger will contain a cylindrical carbonization reactor to be filled with raw biomass. Either syngas or combustion products will be allowed to flow around the reactor. The heat exchanger will be designed in a way to act as a heat accumulator around the reactor to prolong the heat transfer time and in the same time reduce the carbonization duration.
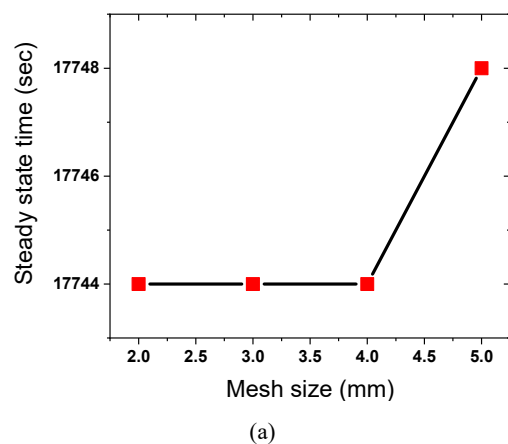
Now the simulation will be performed on a cylindrical reactor. The cylinder has a radius of 75 mm and height of 200 mm. The size of the reactor is relatively small so a 3D simulation will be run during this case.
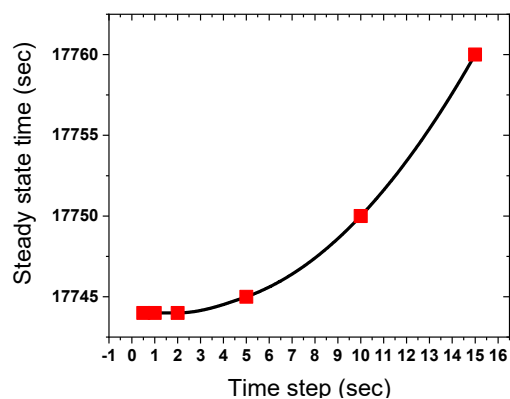
The same processes for mesh size and time step independent solutions will be used like before. For this simulation, all the cylinder's outer surfaces will be assumed to have the same temperature of 500 K which is the approximate exit syngas temperature from the updraft gasifier. The solid inside the cylinder will be assumed to be wood which is initially at 300 K. The same previous code line will be used with changing the target temperature to 495 K. For the mesh size independent solution, a time step will be taken 1 second and 4 different mesh sizes will be used 5, 4, 3 and 2 mm. Fig. 6 (a) is the mesh independent solution result which shows that a 4 mm mesh size will be used. For the time step independent solution, the 4 mm mesh size will be used, and the time steps will be 15, 10, 5, 2, 1 and 0.5 seconds. Fig. 6 (b) shows that a 5 seconds time step is ideal. So, for any simulation concerned with this part the time step will be 5 seconds and the mesh size will be 4 mm. Fig. 6 (c) shows the temperature distribution across the cylindrical reactor which indicates a very good temperature homogeneity which will result in a uniform product.
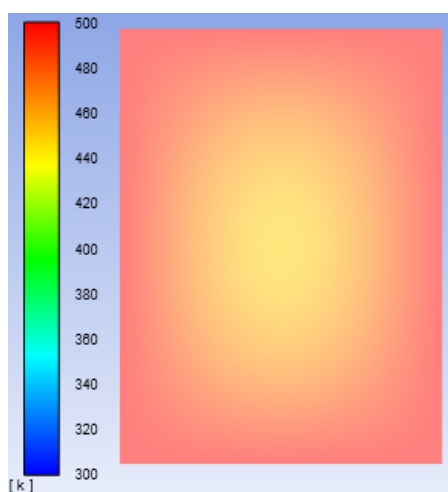
IV. CONCLUSIONS

Three different configurations for a parallel CGC reactor are considered. The novelty in this study is the different arrangements of gasifiers to supply the required heat to the carbonization reactor. The three cases are numerically simulated using Ansys Fluent software after performing mesh and time step independent solutions. The focus of this study was the average temperature distribution inside the carbonization reactor. The carbonization section is common among the three different cases and the difference among them is how this carbonization section is heated. The first case was heated by 2 different gasifiers, the second from syngas from the inner side and combustion from the outer side and finally the third case gasifier on the inner side and combustion products from the outer side. The simulation results showed that only the first design could provide only sectional homogeneous temperature distribution not across the whole reactor. Thus, to have a homogenous product, only small section will be utilized which will reduce the production capacity of the reactor. In order to keep the carbonized product production high, a series configuration is proposed. This series configuration consists of an updraft or downdraft gasifier and a series heat exchanger/accumulator. The heat exchanger takes the syngas and heats the carbonization reactor. If the syngas temperature is low, it can be combusted to produce higher heat. This resulted in a uniform temperature distribution across the whole reactor as it has only one source for heat with no temperature distribution on any surface of the carbonization section. The simulation results indicate that either the first parallel case can be used at a reduced product amount or keep production rate high by using the series configuration. Based on these results a series CGC reactor will be manufactured and experimental testing will be performed in the future work.

(a)

World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:14, No:9, 2020

(b)

(c)

Fig. 6 Results of the mesh independent solution (a), the time step independent solution (b) and temperature profile across a vertical plane of the cylindrical reactor (c)

REFERENCES

[1] P. Basu, *Biomass gasification, pyrolysis and torrefaction: practical design and theory*: Academic press, 2018.
[2] T. Reed and A. Das, "Handbook of Biomass Downdraft Gasifier Engine Systems," 1988.
[3] J. Twidell and T. Weir, *Renewable energy resources*: Routledge, 2015.
[4] P. McKendry, "Energy production from biomass (part 1): overview of biomass," *Bioresource technology,* vol. 83, pp. 37-46, 2002.
[5] R. Saidur, E. Abdelaziz, A. Demirbas, M. Hossain, and S. Mekhilef, "A review on biomass as a fuel for boilers," *Renewable and sustainable energy reviews,* vol. 15, pp. 2262-2289, 2011.
[6] M. Amer, M. Nour, M. Ahmed, S. Ookawara, S. Nada, and A. Elwardany, "The effect of microwave drying pretreatment on dry torrefaction of agricultural biomasses," *Bioresource technology,* vol. 286, pp. 121400-121400, 2019.
[7] P. McKendry, "Energy production from biomass (part 2): conversion technologies," *Bioresource technology,* vol. 83, pp. 47-54, 2002.
[8] L. Zhang, C. C. Xu, and P. Champagne, "Overview of recent advances in thermo-chemical conversion of biomass," *Energy Conversion and Management,* vol. 51, pp. 969-982, 2010.
[9] M. Patel, X. Zhang, and A. Kumar, "Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review," *Renewable and Sustainable Energy Reviews,* vol. 53, pp. 1486-1499, 2016.
[10] H. Jameel and D. R. Keshwani, "Thermochemical conversion of biomass to power and fuels," in *Biomass to renewable energy processes*, ed: CRC Press, 2017, pp. 375-422.
[11] P. McKendry, "Energy production from biomass (part 3): gasification technologies," *Bioresource technology,* vol. 83, pp. 55-63, 2002.
[12] V. Krishnamoorthy and S. Pisupati, "A critical review of mineral matter related issues during gasification of coal in fixed, fluidized, and entrained flow gasifiers," *Energies,* vol. 8, pp. 10430-10463, 2015.
[13] M. J. Prins, K. J. Ptasinski, and F. J. Janssen, "More efficient biomass gasification via torrefaction," *Energy,* vol. 31, pp. 3458-3470, 2006.
[14] S. Kasaoka, Y. Sakata, and M. Shimada, "Effects of coal carbonization conditions on rate of steam gasification of char," *Fuel,* vol. 66, pp. 697-701, 1987.
[15] K. Ichikawa, J. Inumaru, K. Kidoguchi, S. Hara, M. Ashizawa, and M. Kanai, "Carbonization and gasification of biomass and power generation system," ed: Google Patents, 2005.
[16] K. Umeda, S. Nakamura, D. Lu, and K. Yoshikawa, "Biomass gasification employing low-temperature carbonization pretreatment for tar reduction," *Biomass and Bioenergy,* vol. 126, pp. 142-149, 2019.
[17] L. Ding, K. Yoshikawa, M. Fukuhara, Y. Kowata, S. Nakamura, D. Xin*, et al.*, "Development of an ultra-small biomass gasification and power generation system: Part 2. Gasification characteristics of carbonized pellets/briquettes in a pilot-scale updraft fixed bed gasifier," *Fuel,* vol. 220, pp. 210-219, 2018.
[18] Q.-V. Bach, H.-R. Gye, D. Song, and C.-J. Lee, "High quality product gas from biomass steam gasification combined with torrefaction and carbon dioxide capture processes," *International Journal of Hydrogen Energy,* vol. 44, pp. 14387-14394, 2019.
[19] J. Huang, Y. Qiao, X. Wei, J. Zhou, Y. Yu, and M. Xu, "Effect of torrefaction on steam gasification of starchy food waste," *Fuel,* vol. 253, pp. 1556-1564, 2019.
[20] B. Erlach, B. Harder, and G. Tsatsaronis, "Combined hydrothermal carbonization and gasification of biomass with carbon capture," *Energy,* vol. 45, pp. 329-338, 2012.
[21] A. Tremel, J. Stemann, M. Herrmann, B. Erlach, and H. Spliethoff, "Entrained flow gasification of biocoal from hydrothermal carbonization," *Fuel,* vol. 102, pp. 396-403, 2012.
[22] D. S. Gunarathne, A. Mueller, S. Fleck, T. Kolb, J. K. Chmielewski, W. Yang*, et al.*, "Gasification characteristics of hydrothermal carbonized biomass in an updraft pilot-scale gasifier," *Energy & Fuels,* vol. 28, pp. 1992-2002, 2014.
[23] J. Ma, M. Chen, T. Yang, Z. Liu, W. Jiao, D. Li*, et al.*, "Gasification performance of the hydrochar derived from co-hydrothermal carbonization of sewage sludge and sawdust," *Energy,* vol. 173, pp. 732-739, 2019.
[24] X. Zheng, W. Chen, Z. Ying, J. Huang, S. Ji, and B. Wang, "Thermodynamic investigation on gasification performance of sewage sludge-derived hydrochar: Effect of hydrothermal carbonization," *International Journal of Hydrogen Energy,* vol. 44, pp. 10374-10383, 2019.