Analysis of Pyrolysis Kinetics of Biomass Particle Under Isothermal and Non-Isothermal Heating Conditions using Differential Transformation Method

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Abstract

In this study, differential transformation method is applied to analyze pyrolysis kinetics of biomass particle under isothermal and non-isothermal heating conditions. The developed analytical solutions to the system of pyrolysis kinetic models are used to investigate the effects of heating conditions, heating rates on the pyrolysis residence time and technologies. Also, as means verification, the developed solutions of the kinetic models using differential transformation method are compared with the results of the solutions of exact analytical method. Good agreements are established between the present results and the past works. It is therefore expected that this study will enhance the understanding of the pyrolysis process by giving physical insights into the various factors and the parameters affecting the phenomena.

Index terms— biomass particle; pyrolysis kinetics; isothermal temperature; non- isothermal heating rates; differential transformation method.

1 Introduction

he important and the centrality of pyrolysis process in the thermochemical biomass conversion processes of biomass have increased the research interests in the studies of the energy conversion processes. In the study of biomass gasification processes, although, overall process of pyrolysis appears simple but the sequence of reactions is complex and involves both endothermic and exothermic processes whose thermodynamics and kinetics are poorly understood [1]. Under such complex phenomena, it is impossible to formulate a complete mathematical model of pyrolysis which will still be mathematically tractable. However, as a compromise between mathematical tractability and accuracy of description, simplified models are employed under certain defined conditions to predict the conversion process of biomass particle. In fact, the need for the simple rationally-based models of pyrolysis as a basis for reactor design has been identified in the survey of modeling of pyrolysis of biomass particle, particularly on the studies of the kinetic, thermal and heat transfer effects, Koufopanos et al. [12] assumed the pyrolysis process to be primary and secondary kinetic reactions.

Di Blasi [18] analysed the effects of convection and secondary reactions within porous solid fuels undergoing pyrolysis. Melaaen and Gronli [19] presented models on moist wood drying and pyrolysis. Jalan and Srivastava [20] explored kinetic and heat transfer effects on the pyrolysis of a single biomass cylindrical pellet. Ravi [21] proposed a semi-empirical model for pyrolysis of sawdust in an annular packed bed using pseudo-first order reaction for the chemical reaction of the pyrolysis. In their model, Babu and Chaurasia [22] considered time-dependent density and temperature-dependent specific heat capacity of biomass to investigate the dominant design variables in pyrolysis of biomass particles of different geometries in a thermally thick regime. In the recent time, Sheth and Babu [23], presented Kinetic Model for biomass pyrolysis and concluded that pyrolysis in wood is typically initiated at 200°C and lasts till 450-500°C, depending on the species of wood. Yang et al [24] presented that the major stage of biomass pyrolysis occurs between 250-450 o C. Mandl et al. [25], pointed out in their work that the pyrolysis of softwood pellets takes place at around 425K and char particles and volatiles

are formed while Weerachanchaiet al. [26] submitted that the major decomposition of all biomasses occurred in the range of 250-400 o C. Slopiecka et al. [27], in their studies of poplar wood, concluded that the decomposition of hemicelluloses and cellulose take place in active pyrolysis in the temperature from 473-653K and 523-623K, respectively. They then added that Lignin decomposes in both stages: active and passive pyrolysis in the range from 453-1173K without characteristics peaks.

Studies on the analysis of biomass kinetics have been based on numerical approach because of the non-linear nature of the developed models. However, the classical way of finding analytical solution is obviously still very important since it serves as an accurate benchmark for numerical solutions. Therefore, as a mean of investigating and presenting the exact effects of various parameters in the pyrolysis kinetics thereby increasing the predictive power, this study also presents the analytical solutions of pyrolysis kinetics of biomass particle using differential transform method (DTM). Although, this concept was introduced by ?hou [40], its applications to both linear and non-linear differential and system of differential equation have fast gained ground or appeared in many engineering and scientific research. The potentiality of the method is displayed in the provisions of symbolic or analytical solutions to both linear and non-linear integral and differential equations without linearization, discretization or perturbation. DTM is capable of greatly reducing the size of computational work while still accurately providing the series solution with fast convergence rate.

As good and accurate the method presents itself, to the best of the authors' knowledge, it has not been applied for the study and the analysis of biomass pyrolysis kinetic and thermal decomposition. Therefore, in this study, differential transformation method is applied to study the pyrolysis kinetics of biomass particle under isothermal and non-isothermal heating conditions. Also, through the solutions of the method for the problems under investigation, simulations are carried out to study the effects of pertinent models parameters, isothermal and non-isothermal heating conditions on the pyrolysis kinetics of biomass particles.

Heat is transferred to the biomass particle surface from gaseous surrounding by conduction, radiation and/ or convection and then to the interior of the particle mainly by conduction. The temperature inside the particles increases as the heat penetrates more into the interiors of the solid causing moisture evaporation i.e. drying off the moisture. The rate of drying depends upon the temperature, velocity, and moisture content of the drying gas, as well as the external surface area of the feed material, the internal diffusivity of moisture and the nature of bonding of moisture to that material, and the radiative heat transfer. As the temperature increases, biomass particle decomposes into charcoal, tar and gaseous products. The amounts of each of these products vary depending on the zone temperature, rate of heating, structure, and composition and size of catalysts.

The kinetic scheme as shown in fig. 1 describes the process of pyrolysis (primary and secondary) which involves thermal decomposition of biomass into gases, tar (liquid product of biomass pyrolysis, known as bio-oil or pyrolysis oil) and char, and the tar further decompose into char and gases This two-stage parallel reaction model of biomass pyrolysis has previously been used by other researchers [10, **??**3,17,18,19,21,35]. According to the two-stage parallel reaction model, the biomass undergoes thermal degradation according to primary reactions (k 1 ; k 2 ; k 3) giving gas, tar and char as products. Tar may undergo secondary reactions (k 4 , k 5). This model shows to be the most classical models for wood pyrolysis **??**Prakash and Karunanithi [39].

The kinetic equations of pyrolysis, the heat transfer model and the corresponding initial and boundary conditions are given as(1a) (1b) (1c) (1d)

where

The initial conditions for the kinetic equations are;

For the Isothermal condition, T=T o (3) Srivastava [23] assumed that in the thermogravimetric analysis, the temperature and time have a linear relationship (non-isothermal heating condition).

This therefore led to the appropriate representation to describe the Srivastava's assumption as; (4) where T o is the initial temperature in K, ? is the heating rate in K/s and t is the time in s.

2 Which makes (5)

However, for the sake of cleanliness, the bars are removed in the solutions and the non-dimensionless form of Eqs. (1a-1d) still look like the same equation. In order to avoid seemingly similar equations, the nondimensionless forms of Eqs. (1a-1e) were not written out in this work.

3 III. Method of Solution: Differential Transform Method

The simultaneous kinetic models in Eqs. (1a)-(1d) are solved using differential transformation method as introduced by Zhou **??** ? ? = = ? ? ? ?**(8)**

where p U is called the spectrum of) (tu at i t t = Expressing) (t u in Taylor's series as ( ) ( ) ( ) ! p i p t t u t U p p ? ? ? ? = ? ? ? ? ? ? ?**(9)**

where Equ. (9) is the inverse of) (k U us symbol 'D' denoting the differential transformation process and combining (8) and (9), we havet T T o ? + = ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? =) (exp t T R E A k o i i i ? 5 1? = i ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? = o i i i RT E A k exp 5 1? = i T B T C k k C k t C) (5 4 2 + ? = ? ? ? T B C C k C k t C 5 3 ? + = ? ? T B G C k C k t C 4 1 ? + = ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? = RT E A k i i i exp 5 1? = i Year 2017 Global Journal of Researches in Engineering ( ) Volume XVII Issue VI Version I

A B B C k k k t C) (3 2 1 + + ? = ? ? , , 0 0 B B C C t = = 0 = = = T G C C C C (2) Bo B B C C C = Bo C C C C C 2 2 = Bo G G C C C 1 1 = Bo C C C C C 1 1 = Bo G G C C C 2 2 = Bo C C C C C 2 2 =**(6)**

The above kinetic models were non-dimensionalized as using the following dimensionless parameters;for i t t = , then (,) (,) i t p t p ? ? =

, where p belongs to the set of non-negative integers, denoted as the p-domain. We can therefore write Eq. (7) as ( ) 1 0 ( ) ( ) ( ) ! p i p t t u t U p D U p p ? ? = ? ? ? = = ? ? ? ? ? ? ? (10)cos t ? ? + ( ) ( ) U p V p ± ( ) U p ? (1) (1) p U p + + 0 ( ) ( ) p r V r U p r = ? ? 1 0 ( ) ( ) p m r U r U p r ? = ? ? ( )( ) ( ) ( ) 1 2 p p p n U p n + + + + ? sin p! 2! p p ? ? ? ? ? + ? ? ? ? ( ) cos p! 2! p p Z p ? ? ? ? ? = + ? ? ? ?

Using the operational properties of the differential transformation method, the differential transformations of Eqs. (1a)-(1d) under isothermal condition are) ( ) 1 ( ) 1 (3 2 1 p C p k k k p C B B + + + ? = + (11a)) ( ) 1 ( ) ( ) ( ) 1 ( ) 1 (5 4 2 p C p k k p C p k p C T B T + + ? + = + ? (11b)) ( ) 1 ( ) ( ) 1 ( ) 1 (5 3 p C p k p C p k p C T B C + + + = + ? (11c)) ( ) 1 ( ) ( ) 1 ( ) 1 (4 1 p C p k p C p k p C T B G + + + = + ? (11d)

The solutions of the of the kinetic equations for the isothermal condition are given as follows:

The analysis of) 1 (+ p C B : From Equ. (11a), we have) (1) ( ) 1 (3 2 1 p C p k k k p C B B + + + ? = + Global Journal of Researches in Engineering ( ) Volume XVII Issue VI Version I 4 Year 2017 A 1 2 3

(1) ( )B Bo C k k k C = ? + + , 2 1 2 3 ( ) (2) 2 B Bo k k k C C + + = , 3 1 2 3 ( ) (3) 6 B Bo k k k C C ? + + = 4 1 2 3 ( ) (4) 24 B Bo k k k C C + + = , 5 1 2 3 ( )**(5)**

, 120B Bo k k k C C ? + + = 6 1 2 3 ( ) (6) 720 B Bo k k k C C + + = 7 1 2 3 ( )**(7)**

, 5040 B Bo k k k C C ? + + = 8 1 2 3 ( ) (8) 40,320 B Bo k k k C C + + = ,. . . 1 2 3 ( ) ( ) (1) ! n n Bo k k k C n C n + + = ? n B B B B B B B B B B B t n C t C t C t C t C t C t C t C t C C t C) (...) 8 ( ) 7 ( ) 6 ( ) 5 ( ) 4 ( ) 3 ( ) 2 ( ) 1 ( ) 0 ( ) (+ + + + + + + + + + + = (12)

After substituting the results in the above analysis into Eq. (**??**2), we have[ ] 24) (6) (2) ( ) ( ) (4 4 2 1 3 3 3 2 1 2 3 2 1 3 2 1 ? ? ? ? ? ? + + + ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? + + + + + ? = t C k k k t C k k k t C k k k t C k k k C t C Bo Bo Bo Bo Bo B ( ) ( ) ( ) 320 ,**40**) (5040 720 6 120 8 8 3 2 1 7 7 3 2 1 6 3 2 1 5 5 3 2 1 ? ? ? ? ? ? + + + ? ? ? ? ? ? ? + + ? + + + ? ? ? ? ? ? ? + + ? t C k k k t C k k k t C k k k t C k k k Bo Bo Bo Bo ... 000 1307674368) (0 8717829120) (6227020800) (479001600) (39916800) (3628800) (362880) (15 3 2 1 14 3 2 1 13 3 2 1 12 12 3 2 1 11 11 3 2 1 10 10 3 2 1 9 9 3 2 1 + ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? + + + ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? + + + ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? + + + ? ? ? ? ? ? ? + + ? t C k k k t C k k k t C k k k t C k k k t C k k k t C k k k t C k k k Bo Bo Bo Bo Bo Bo Bo (13)

Which can be written as ( ) ( ) ( ) ( ) ( ) ( ) ( )**2**B Bo k k k k k k k k k k k k t t t t k k k k k k k k k k k t t t t C t C k k k k k k k k k k k t t t + + + + + + ? + + + ? + + + + + + + + + + ? + ? + = + + + + + + + ? + ? + 12 12 3 13 14 13 14 15 1 2 3 1 2 3 1 2 3) 479001600 ( ) ( ) ( ) ... 6227020800 87178291200 1307674368000 k t k k k k k k k k k t t t ? ? ? ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? + + + + + + ? ? ? + ? + ? ?**(14)**

Equ. (14) can be written as ( )1 2 3 ( ) 0 1 2 3 0 (1) ( ) ( ) e ! p N k k k t p p B Bo Bo p C t C k k k t C p ? + + = ? = + + = ?**(15)**

The analysis of) 1 (+ p C T : From Equ. (11b)) ( ) 1 ( ) ( ) ( ) 1 ( ) 1 (5 4 2 p C p k k p C p k p C T B T + + ? + = + ?

On analyzing the differential transform in Eq. (11b), we have A Therefore, the differential transformation solution of C T is given as2 (1) T Bo C k C = 2 1 2 3 2 4 5 ( ) ( ) (2) 2 2 T Bo k k k k k k k C C ? + + + ? ? = ? + ? ? ? ? Year 2017 Global Journal of Researches in Engineering ( ) Volume XVII Issue VI Version I A 2 2 2 1 2 3 1 2 3 4 5 2 4 5 ( ) ( ) [( )] (3) ( ) 3 6 6 T Bo k k k k k k k k k C k k k C ? ? ? ? ? ? ? ? + + + + + ? ? ?? = + + + ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ? ? 2 3 3 2 1 2 3 4 5 1 2 3 2 4 5 2 4 5 ( ) 3 ( ) ( ) ( ) (4) 24 4 6 ( ) [( )] 6 T Bo k k k k k k k k k k k k k C C k k k k k ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? + + + ? + + ? ? ? = ? + ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? + + ? ? ? ? ? ?? + ? ? ? ? + ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 3 2 1 2 3 2 2 1 2 3 4 2 1 2 3 4 5 4 5 1 2 3 2 4 5 2 4 5 ( ) 24 ( ) 3 ( ) ( ) (5) ( ) 120 5 ( ) 4 6 ( ) [( )] 6 T k k k k k k k k k k k k k k C k k k k k k k k k k ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? + + + ? ? ?? ? ? = + ? ? ?? ? ? + ? + + ? ? ? ? ? ? ?? + ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? + + ? ? ? ? ? ?? ? ? + ? ? ? ? ? ? ? + ? Bo C ? ? 5 2 1 2 3 4 2 1 2 3 3 2 1 2 3 2 2 1 2 3 4 5 4 5 4 5 1 2 3 2 4 5 2 4 5 ( ) 720 ( ) 120 ( ) 24 (6) ( ) ( ) 3 ( ) 6 ( ) 5 ( ) 4 6 ( ) [( )] 6 T k k k k k k k k k k k k C k k k k k k k k k k k k k k k k k k ? ? ? ? ? + + + + ? ? + + ? ? ? ? ? = ? ? ? ? ? + + + + ? ? ? ? + ? ? ? ? + ? ? ? ? + ? + + ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? ? ? ? ? + ? ? ? ? ? + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? Bo C ?2 3 4 5 6 ( ) (0) (1) (2) (3) (4) (5) (6) ... ( ) n T T T T T T T T T C t C C t C t C t C t C t C t C n t = + + + + + + + + (**16**)

The analysis of (1)C C p + : From Equ. (11c) 3 5 (1) ( ) ( ) (1)**(1)**C B T k k C p C p C p p p ? + = + + +

Analyzing Eq. (11c) as before, we have 3 (1) C Bo C k C = , 3 1 2 3 3 5 ( ) (2) 2 2 C Bo k k k k k k C C ? + + ? ? = ? ? ? ? ? ? 2 2 3 1 2 3 1 2 3 3 5 3 5 ( ) ( ) [ ] (3) 3 6 6 C Bo k k k k k k k k k C k k C ? ? ? ? ? ? ? ? + + + + ? ? ?? = ? + ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ? ? ( ) 2 3 1 2 3 3 1 2 3 3 1 2 3 3 5 3 5 2 3 5 ( ) 3 ( ) ( ) (4) 6 24 4 6 C Bo k k k k k k k k k k k k k C C k k k k ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? + + ? ? ? ? = ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? + ? ? ? ? ?? ? ? ? ? + ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ( ) 3 3 1 2 3 2 3 1 2 3 4 3 1 2 3 3 5 1 2 3 3 5 3 5 2 3 5 ( ) 24 ( ) 3 ( ) (5) ( ) 120 5 6 4 6 C Bo k k k k k k k k k k k k k k

C C k k k k k k k k k ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? + + ? ? ?? ? ? = ? ? ? ?? ? ? ? + + ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ?C k k k k k k k k k k k C k k k k k k k k k k k k k k k k ? ? ? ? ? + + ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? + + = ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ?? ? ? ? + + ? Bo C ?

Analysis of Pyrolysis Kinetics of Biomass Particle Under Isothermal and Non-Isothermal Heating Conditions using Differential Transformation Method and so on

The differential transformation solution of C C is given as2 3 4 5 6 ( ) (0) (1) (2) (3) (4) (5) (6) ... ( ) n C C C C C C C C C C t C C t C t C t C t C t C n t = + + + + + + + + (**17**)

The analysis of (1)C C p + : From Equ. (11d)**1 4**

(1) ( ) ( )

(1)G B T k k C p C p C p p p ? + = + + +

On analyzing Eq. (26d) as before, we have1 (1) G Bo C k C = 1 1 2 3 1 4 ( ) (2) 2 2 G Bo k k k k k k C C ? + + ? ? = ? ? ? ? ? ? © 2017 Global Journals Inc. (US) ( ) 2 2 1 4 1 1 2 3 1 2 3 1 4 ( ) ( ) (3) 3 6 6 G Bo k k k k k k k k k C k k C ? ? ? ? ? ? ? ? + + + + ? ? ?? = ? + ? ? ? ? ?? ? ? ? ? ?? ? ? ? ? ? ? ( ) 2 1 1 2 3 3 1 2 3 1 1 2 3 1 4 1 4 2 1 4 ( ) 3 ( ) ( ) (4) 6 24 4 6 G Bo k k k k k k k k k k k k k C C k k k k ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? + + ? ? ? ? = ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? + ? ? ? ? ?? ? ? ? ? + ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? Global Journal of Researches in Engineering ( ) Volume XVII Issue VI Version I 8 Year 2017 A ( ) 3 1 1 2 3 2 1 1 2 3 4 1 1 2 3 1 4 1 2 3 1 4 1 4 2 1 4 ( ) 24 ( ) 3 ( ) (5) ( ) 120 5 6 4 6 G Bo k k k k k k k k k k k k k k C C k k k k k k k k k ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? + + ? ? ? ? ? ? + + ? ? ?? ? ? = ? ? ? ?? ? ? ? + + ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ? ?? ? ? ? ? ? ? ? ? ?

Analysis of Pyrolysis Kinetics of Biomass Particle Under Isothermal and Non-Isothermal Heating Conditions using Differential Transformation Method ( )5 1 1 2 3 3 1 1 2 3 2 1 1 2 3 4 1 1 2 3 1 4 1 4 1 2 3 1 4 1 4 2 1 4 ( )**720**( ) 24 ( ) (6) 3 ( ) ( ) 6 120 5 6 4 6 G k k k k k k k k k k k k C k k k k k k k k k k k k k k k k ? ? ? ? ? + + ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ? ? ? + + = ? ? ? ? ? ? + + ? ? ? ? ? ? ? ? ? ? ?? ? ? ? + + ? Bo C ?

and so on

The differential transformation solution of C C is given as2 3 4 5 6 ( ) (0) (1)**(2) (3) (4) (5) (6)**... ( ) n G G G G G G G G G C t C C t C t C t C t C t C n t = + + + + + + + +**(18)**

For the purpose of verifying the solution of the differential transformation method, exact analytical solutions using Laplace transform have been developed for Eqs. (1a)-(1d) subject to isothermal condition as (19a) (19b) (19c) ( ) 1 2 3 ( ) e k k k t B Bo C C ? + + = ( ) ( ) 1 2 3 4 5 ( ) ( ) 2 4 5 1 2 3 e e ( )**(**) k k k t k k t Bo T k C C k k k k k ? ? ? + + ? + ? ? ? ? ? ? = + ? + + ( )**( ) ( ) ( ) ( ) ( ) (**)k k k t k k t k k k t C Bo k k k k k k k C C k k k k k k k k ? ? ? ? ? + + ? + ? + + ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? + + + ? ? ? ? ? ? = ? ? ? + + + ? + + ? ? ? ? ? ? ? ? ? Year 2017

Global Journal of Researches in Engineering ( ) Volume XVII Issue VI Version I A

( ) 1 2 3 4 5 1 2 3 ( ) ( ) 2 4 ( ) 1 2 3 4 5 1 1 2 3 4 5 1 2 3 1 e 1 e ( ) 1 e ( ) ( ) ( ) k k k t k k t k k k t G Bo k k k k k k k k C C k k k k k k k k ? ? ? ? ? + + ? + ? + + ? ? ? ? ? ? ? ? ? ? ? + ? ? ? ? + + + ? ? ? ? ? = ? ? ? + + + ? + + ? ? ? ? ? ? ? ? ?

4 Results and Discussion

According to the two-stage parallel reaction model used in this work, as the pyrolysis zone temperature increases, the biomass undergoes thermal degradation according to primary reactions giving gas, tar and char as products. Tar also undergoes secondary reactions to give gas and tar. Since the amounts of each of these products vary depending mainly on the zone temperature, the influences of heating conditions on the particle residence time and pyrolysis yield are studied using the differential transformation method. Figs. 2-21 show the effects of isothermal heating temperatures on the particle resident time. Also, the figures demonstrate the agreement between the exact analytical solutions and the approximate analytical solutions developed by using differential transformation method. Figs. **??**2-25 show the effects of isothermal heating temperature (where the pyrolysis temperature is maintains a selected constant temperature in a pyrolyzing chamber) on the pyrolysis yield. From the results, thermal decomposition takes more time at temperature of 473 K and 573 K than that of higher isothermal heating temperature for the biomass particle of the same size. The figures clearly depict that low temperature pyrolysis produces more char and high temperature pyrolysis enhances the production of gas and tar, i.e. an increase in the isothermal heating temperature increases the yield of gaseous products and the decreases char production. The reduced production of tar and gas at low isothermal heating temperature may be due to some resistances to mass or heat transfer inside the particles of the biomass which can be broken by high heating temperature thereby resulting in greater primary decomposition of the sample and higher production of gas and tar at the higher temperature. In each case of the isothermal heating, as the pyrolysis reaches completion, the char production becomes constant. Also, the results show that the tar rate yield increases first and then decreases and the gas yield increases as the pyrolysis temperature increases, but the char yield significantly decreases as the isothermal

temperature increases to 573K and 673K. The decrease in the tar yield and sudden increase of gas yield observed at higher temperature may be due to secondary cracking of the pyrolysis liquid in to gaseous product at higher temperature. It could also be deduced from the results that the time required to obtain a certain conversion level decreases with increasing isothermal heating temperature. The trends obtained in this work as shown above are qualitatively the same as reported in literature [24] and [25].

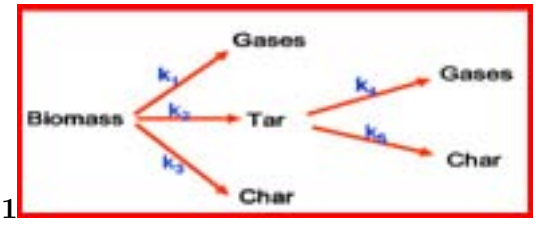
As pointed out in the previous section, heating rate is one of the important parameter for the yield of different products from the pyrolysis process. To determine the effects of heating rate on the yields of the biomass pyrolysis, simulations were carried out for different heating rates of as shown in Figs. 26 38-41 show the effects of non-isothermal temperature on pyrolysis yields as a function of temperature at an initial particle temperature of 373 K. From the figures, the drying or pre-pyrolysis process are shown as zero rate of production and conversion of the products from 0-120 s and 303-473 K which validates the fact that pyrolysis process actually commenced at about 473K as stated in literatures [25]. It is surprising to see that at any heating rate, the production rate of char is higher than that of tar and gas. This may be due to the increase in the resistance for mass and heat transfers offered by the thick layer of the dried biomass i.e. for the gas and tar to evolve from the particle, they have to travel through a dried layer of the biomass which in consequence, comparably reduces their production rates. Also, it should be noted that increasing the heating rates reduces the particle residence time and as the heating rate are increased, the residence time of volatiles at low or intermediate temperatures decreases. Most of the reactions that favour tar conversion to gas occur at higher temperatures. At low heating rates, the volatiles have sufficient time to escape from the reaction zone before significant cracking can occur. Also, most of the decomposition takes place at temperatures lower than 500 K, and no more significant decomposition is produced above 750 K.

effects of non-isothermal temperature on pyrolysis yields On comparing these results with that of isothermal heating conditions, it is shown that the amount of char produced in the non-isothermal heating conditions is lower than in the isothermal heating conditions. This is because the isothermal conditions were carried out at relative low temperature and the residual solid contains compounds that evaporate at higher temperatures. The tar yield was low at lower heating rate and slightly increases with increase in heating rate. The gas yield increases with increase in heating rate while the char yield decreases significantly yield with the increase of heating rate may be due to some resistances to mass or heat transfer inside the particles of the biomass, but increasing the heating rate breaks the heat and mass transfer limitation in the pyrolysis and thereby increasing the tar yield and decreasing char formation.

with increase in heating rate. The increasing of the tar 41, the rate of char production increases gradually between the particle temperatures of 500 K and 573 K, and as the particle temperature increases, as gases and tar evolve from the biomass particle and consequently, the rate of char production increases rapidly from the particle temperature of 500 K to 723 K, after which there is a decrease in the production rate of char (due to the loss of H and O contents of the char at high temperatures) till the whole wood has been pyrolysed. This shows that pyrolysis process is slowed down from 723-873 K (depending on the heating rates). It could also be inferred from the results that the primary pyrolysis rate of tar production starts gradually from about 573 K till 753 K (depending on the heating rates) and then increases rapidly till the whole tar has been converted to char and gas at the final pyrolysis temperature. The extension of the rate-temperature figure to the negative portion of the graph depicts the conversion rate of tar to char and gas.

5 c) Effects of heating rates on particle residence time

Recently, Lédé , and Authier [32] advocated for the criteria for characterizing fast pyrolysis based on temperature and heating rate of solid particles that undergoes a thermal decomposition The effects of heating rates on the particle residence time are shown in Figs. **??**2-45. For the low heating rates of 0.01-0.1K/s in Figs. 42, it takes hours or days for the pyrolysis to occur and this will definitely enhance the production of charcoal as depicted in Table 4. As the heating rates increases, the particle residence time in the reactor decreases and high heating rates favours the production of tar and gas. Therefore, as shown in the table, the length of heating and its intensity affect the rate and extent of pyrolytic reactions, the sequence of these reactions, and composition of the resultant products. [1] [2]



1

Figure 1: Fig. 1 :

3

properties of differential transformation method

S/N	Function	Differential Transform
1	( ) ( ) u t v t ±	
2	? ( ) u t	
3	( ) du t dt	
4	( ) ( ) u t v t	
5	( ) u t m	
6	( ) d u t n dx n	
7	(sin t ? ? +	)
8	( )	

Figure 2: Table 3 :

Year 2017
6
( ) Volume XVII Issue VI Version I
Global Journal of Researches in Engineering

and so on

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Figure 3:

2

Figure 4: Table 2 :

3

[Note: IV.]

Figure 5: Table 3 :

4

Pyrolysis technology	Residence time	Heating rate	Temperature (o C)	Product
Carbonization	days	very low	400	charcoal
Conventional	5-30 min	low	600	oil, gas, char
Fast	0.5-5s	very high	650	bio-oil
Flash-liquid	$<$ 1s	high	$<$ 650	bio-oil
Flash-gas	$<$ 1s	high	$<$650	chemicals, gas
Ultra	$<$ 0.5s	very high	1000	chemicals, gas
Vacuum	2-30 s	medium	400	bio-oil
Hydro-pyrolysis	$<$ 10s	high	$<$ 500	bio-oil
Conventional	$<$ 10s	high	$<$ 700	chemicals

Figure 6: Table 4 :

[1]

[2]Analyzing the differential transform in Eq. (11a), we have Applying the inverse differential transform,

5 C) EFFECTS OF HEATING RATES ON PARTICLE RESIDENCE TIME

.1 Global

A study the effects of heating conditions, heating rates on the pyrolysis residence time and technologies. Good agreements were established between the present results and the past works. It is therefore expected that this study will enhance the understanding of the pyrolysis process by giving physical insights into the various factors and the parameters affecting the phenomena.

V.

.2 Conclusion

In this work, differential transformation method has been applied to analyze pyrolysis kinetics of biomass particle under isothermal and non-isothermal heating conditions. The developed analytical solutions to the system of pyrolysis kinetic models were used to Nomeclature A1; A2; A3; A4; A5 frequency factor, 1/s Bi m Modified Biot number C concentration, kg/m 3 C p specific heat capacity, J/kgK E activation energy, J/mol h convective heat transfer coefficient, W/m 2 K K thermal conductivity, W/mK k 1 ; k 2 ; k 3 ; k 4 ; k 5 rate constants, 1/s Q heat of pyrolysis, J/Kg r radial distance, m R radius for cylindrical particle, m R g universal gas constant, J/mol t time, s T f reactor final temperature, K T temperature, K R '

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