

# Modeling Drying and Pyrolysis of Moist Wood Particles at Slow Heating Rates

Avdhesh K. Sharma

**Abstract**—Formulation for drying and pyrolysis process in packed beds at slow heating rates is presented. Drying of biomass particles bed is described by mass diffusion equation and local moisture-vapour-equilibrium relations. In gasifiers, volatilization rate during pyrolysis of biomass is modeled by using apparent kinetic rate expression, while product compositions at slow heating rates is modeled using empirical fitted mass ratios (i.e., CO/CO<sub>2</sub>, ME/CO<sub>2</sub>, H<sub>2</sub>O/CO<sub>2</sub>) in terms of pyrolysis temperature. The drying module is validated fairly with available chemical kinetics scheme and found that the testing zone in gasifier bed constituted of relatively smaller particles having high airflow with high isothermal temperature expedite the drying process. Further, volatile releases more quickly within the shorter zone height at high temperatures (isothermal). Both, moisture loss and volatile release profiles are found to be sensitive to temperature, although the influence of initial moisture content on volatile release profile is not so sensitive.

**Keywords**—Modeling downdraft gasifier, drying, pyrolysis, moist woody biomass.

## I. INTRODUCTION

THE importance of thermo-chemical response of lignocellulosic materials in the biomass gasifiers has been recognized in recovering the producer gas as fuel, which in turn can be used for thermal (via burner) or motive power (via gas-turbine or gas-engine) applications. As lignocellulosic material, such as biomass, is exposed to hot environment, it undergoes the gasification processes, more specifically drying, pyrolysis and gasification or combustion processes. Biomass pyrolysis (or thermal decomposition) process yields the “volatiles”, solid substrate “char” and ash residue, which have wide domestic and industrial importance; the volatile gases can be used for power applications, process heating or it can be synthesized to yield methanol, whereas the tarry liquid “pyrolysis oil” can be upgraded to hydrocarbon fuels for Internal Combustion (I.C.) engines. The solid substrate char can be used in metallurgical industry or as cooking fuel for domestic applications [1]. The level of moisture content in biomass feedstock may affect the overall process by altering charring rate, composition of the volatile products and the maximum devolatilization rate. It increases not only the ignition time, but also the minimum intensity of both piloted and spontaneous ignition and the total ignition energy as well [2]. Thus, drying and pyrolysis process plays a significant role on combustion and gasification products and their energetics as well.

Numerous studies are dedicated to model complex process of

biomass drying with emphasis on different aspects/approaches. Bryden et al. [3] suggested the four basic approaches to model drying process of biomass under different combustible conditions. Among them, energy balance approach is the simplest one, herein drying front is considered to be substantially thin and an energy sink maintaining at 373 K accounts for the impact of heat of vaporization in energy balance. In second approach, the drying process of woody particles can be modeled as Arrhenius type. Third method is based on algebraic expression relating the moisture content and temperature by using equilibrium moisture content of atmosphere of saturated steam. Forth approach includes diffusion-controlled modeling for biomass drying at low temperature (<473 K).

Each approach has its own merits and demerits. In energy balance approach, the drying region is confined to a very thin moving surface which cannot be used for modeling drying and pyrolysis of small particles, especially when the thickness drying zone (i.e., control volume) cannot be very thin compared to the material thickness. The prime advantage of employing an Arrhenius-type expression for particles drying is that many different physical phenomena can be considered to be lumped together into a single relation. In the algebraic models, the drying of wood at temperatures less than 373 K is completely neglected. Moreover, it is not likely that equilibrium moisture conditions exist within a wet wood exposed to combustion conditions. Further, model based on diffusion-controlled rates accounts for both evaporation and re-condensation within the biomass particle bed [3]. Those drying models, which are based on the Fick’s law of diffusion, can be used to forecast the wood drying process.

Few authors, including [4], have considered modeling of wood drying process as an inverse problem, i.e. to determine surface emission coefficients and diffusion. Melaaen and Gronli [5] reported a transient equilibrium model to simulate drying of moist wood, while Di Blasi [6] has published a detailed mathematical model for bio-fuels exposed to radiative and convective environment; this model considered moisture evaporation and detailed treatment of transport phenomena to study dynamic behaviour of drying of bio-fuel materials and to evaluate the validity of simplified theories for moisture evaporation processes.

Much work has already been reported to describe thermal degradation of biomass either as a single homogeneous material or the combined decomposition scheme of its major

Avdhesh Kr. Sharma is with the D.C.R. University of Science and Technology, Murthal (Sonapat) -131039, Haryana, India (phone: 0-91-9416722212; e-mail: avdhesh\_sharma35@yahoo.co.in)

constituents viz., cellulose, hemicellulose and lignin [6]-[8]. These studies describe the complex pyrolysis in two stages: (1) primary reactions in respect of virgin solid biomass degradation, and (2) secondary reactions of evaluated degradation products. In general, kinetic studies can be classified as one step global models (i.e., constant ratio between char and volatiles is considered), multi reaction models (herein several reactions are modeled in order to correlate the data) and semi-global models (these include both reactions namely primary and secondary as well). In most studies of general treatment, the volatile release can be represented by a single pseudo-first order reaction. In combustion like environment having thermally thick particles, the release of volatile matters takes place within the temperature gradient in the particles; the volatiles composition may be altered on their way out of the feedstock particle. Thus, Thunman et al. [9] outlined the composition of biomass volatiles on the basis of experience as CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, methane equivalent or light hydrocarbons and heavy hydrocarbons (lumped hydrocarbons or tar). Grobksi and Bain [10] also quoted interesting work on volatile break-up of in CO<sub>2</sub>, H<sub>2</sub>O and CH<sub>4</sub> based on elemental balance. Recently, Sharma *et al.* [11] presented a simplified pyrolysis product composition model for woody biomass materials at low heating rates in order to compute heat of pyrolysis, product composition of volatiles and char. They reported that the pyrolytic energetic transforms from endothermic to exothermic with temperature, while this trend reverts as tar yield falls to zero.

Despite the predictable effects of moisture evaporation of moist wood on charring, volatile products, gas-phase oxidation of volatile matters; the drying processes of biomass in gasifier and combustion modeling are usually neglected [2]. Thus, a simplistic model for drying and pyrolysis process has been developed to understand the thermal degradation behaviour of moist wood particles in a biomass gasifier. Drying of moist biomass is described by mass and heat transfer between the solid biomass particles and surrounding gaseous medium. Pyrolysis module describes the pyrolytic yields at slow heating rates, devolatilization rate and volatile composition in terms of bed temperature and overall biomass consumption rate. For modeling the effect of initial moisture content on moisture loss profile and volatile release profile; the drying and pyrolysis modules have been integrated. Results show that the moisture loss profile and the volatile release profile are highly sensitive to the high temperatures, while the role of initial moisture content is found to be less sensitive on the volatile release profile.

## II. MODEL DESCRIPTION

For fuel beds constituted of thermally thin (pulverized fuel) particles at slow heating rates, the temperature gradient within the particles is negligible, the processes of mass loss - drying, pyrolysis and char burn can be described in sequence, although, char burn lasts much longer than the devolatilization and drying processes. While temperature gradient inside the particles exists in case of thermally thick particles, the drying and devolatilization can be described simultaneously. The moisture is evolved from inner side of the particle while volatiles are

being driven off near the outer shell of the particle. Due to the pressure in the fuel pores during devolatilization of the outer layer of the particle, some of the moisture is forced towards center of the particle until the pressure builds up throughout the particle. Thus, drying process of relatively large particle initially shows inward movement of the water vapor besides the outward movement. The pyrolysis front initiates at the outer edge, which slowly moves in inward direction forming char and releasing volatile matters. As the process of moisture and volatile release proceeds towards completion, the char surface reaction initiates [12]. For the present work, where the granular bed constituted from biomass particle having half-thickness about 20 mm, the pyrolysis phenomenon is assumed to be in thermally thick regime and variation in moisture content may affect the pyrolysis time, while the product yields can be assumed to be independent with moisture content [3]. In this light, the moisture transfer and pyrolysis modules are developed as described by the subsequent sections.

### A. Modeling of Drying Process

Physically, biomass drying takes place owing to two processes: heat transfer and mass transfer between the biomass particle and the surrounding gaseous medium. The mechanism of transfer to woody biomass accounts for diffusion through the fluid film surrounded to the solid particles and diffusion process through the pores in internal (adsorption) sites. In actual process, the physical adsorption takes place almost instantaneously, and equilibrium is considered between particle surface and surrounding fluid envelope. As wet biomass particles encounter the air with relatively low humidity, the biomass particles initiate release of moisture with the surrounding air until equilibrium is attained. Herein, a testing zone in gasifier bed has been considered, where bed porosity and the bed temperature are assumed to be uniform. The testing zone was divided into several control volumes. For model development, following assumptions are invoked as:

1. Particle shrinkage due to moisture evaporation is minor.
2. Testing bed is isotropic with spherical particles of uniform diameter.
3. Neglect the temperature variation within the moist biomass particles.
4. As the thermal diffusivities are higher in magnitude than mass diffusivities, followed by assumption of thermal equilibrium between the solid particle surface and the surrounding fluid envelope in each control volume, implying that heat transfer is much faster than the mass transfer.

Therefore, mass transfer determines the rate of moisture removal from the biomass particles to the gases (air) flowing around them. In order to compute the mass transfer rate, the analytical solution for 1-dimensional mass diffusion equation for spherical particle of wood [13] can be written as:

$$\frac{MC_{in} - MC_{eqb}}{MC_{out} - MC_{eqb}} = \frac{8}{\pi^2} \left( e^{-a_1\beta} + \frac{1}{9} e^{-9a_1\beta} + \dots \right) \quad (1)$$

where, MC is the mass fraction of moisture in wood, and

subscripts *in*, *out* and *eqb* stand for the inlet, outlet and equilibrium values of the moisture fraction in a control volume. The above solution corresponds to the boundary condition  $MC = MC_{eqb}$  at the particle surface.  $a_1$  stands for the first Eigen value with value of  $(\pi/2)^2$ .  $\beta$  designates to Fourier number ( $= D\Delta t_{res} / r_p^2$ ), where  $D$  is the diffusion coefficient for moisture through wood,  $\Delta t_{res}$  is the particle residence time in the control volume of interest and  $r_p$  is the particle radius. Empirical expression of Simpson [14] that gives the dependence of the diffusion coefficient on the moisture content and temperature of the particle is used in the present work. Residence time of biomass particle in a control volume is determined from the flow rate of biomass through the gasifier and the size of the control volume of interest as:

$$\Delta t_{res} = M_b / \dot{m}_b \quad (2)$$

where  $M_b$  is the mass of biomass in control volume of interest, while  $\dot{m}_b$  is the mass flow rate of biomass at inlet of Control volume. The equilibrium moisture content of wood at any point depends on the temperature of wood and the relative humidity of the air that flows over it. Simpson [15] presents a relationship for the equilibrium moisture content as a function of temperature and relative humidity as:

$$MC_{eqb} = \frac{1800}{W} \left( \frac{Kh}{1-Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + 2K_1K_2K^2h^2} \right) \quad (3)$$

where,  $h$  is the relative humidity of the air stream defined as

$$h = \frac{\omega_{air}}{\omega_{air,sat}} = \frac{\omega_{air}}{p_{v,sat}mw_w / p_a mw_{air}} \quad (4)$$

here  $p_{v,sat}$  is the saturation vapour pressure of water vapour at the temperature of air,  $p_a$  is the pressure at which the air flows, and in this case, it is the ambient pressure.  $mw_w$  and  $mw_{air}$  are the molecular weights of water and air, respectively. The  $\omega_{air}$  is the specific humidity (in kg of water vapour per kg of dry air) of the inflow. Coefficients  $K$ ,  $K_1$ ,  $K_2$  and  $W$  are related to temperature, which is obtained from adsorption model [15].

$$\begin{aligned} W &= 349 + 1.290 T + 0.0135 T^2 \\ K &= 0.8050 + 0.000736 T - 0.00000273 T^2 \\ K_1 &= 6.270 - 0.00938 T - 0.000303 T^2 \\ K_2 &= 1.910 + 0.0407 T - 0.000293 T^2 \end{aligned} \quad (5)$$

The saturation vapour pressure is obtained from Antoine equation using vapour pressure data [16], [17] as:

$$\log_{10}(p_{v,sat}) = A - B/(T + 273 + C) \quad (6)$$

here, the vapour pressure is in bar and temperature  $T$  ( $^{\circ}C$ ). The values of constants  $A$ ,  $B$  and  $C$  in eqn. (6) are listed in Table I. The same has been used within the temperature ranges

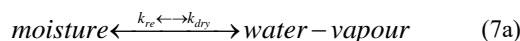
encountered in the drying and preheat zone.

TABLE I  
ANTOINE EQUATION COEFFICIENTS FOR SATURATED VAPOUR PRESSURE [18]

Temperature range(K)	A	B	C
255.8 – 373.0	4.65430	1435.264	-64.848
379 – 573.0	3.55959	643.748	-198.043

The value of  $MC_{in}$  is available from the upstream control volume, and  $MC_{eqb}$  is computed using above method from eqn. (3). With the information of residence time and diffusivity, the right-hand side of eqn. (1) is calculated (as higher order terms are neglected). This gives  $MC_{out}$ , the moisture mass fraction of the biomass at control volume outlet. Mass balance among dry biomass, water vapour in air and moisture in biomass is used input to compute the relevant mass flow rates at the outlet of the control volume, from the knowledge of those at the inlet of the control volume. This process is repeated for each control volume in the zone in sequence.

In order to test the above moisture transfer model, an Arrhenius-type kinetic model accounted for the influence of re-condensation has been used in this work.



Re-condensation of water vapour within un-reacted regions of wood can be modeled as water vapour exists in supersaturated state and is condensed at a rate proportional to the mass flux of water vapour,  $G_{vap}$  following [3]. Thus, net rate of production of water vapour  $\dot{\omega}_{vap}$  can be expressed as:

$$\dot{\omega}_{vap} = \dot{\omega}_{dry} - \dot{\omega}_{re} \quad (7b)$$

If drying temperature goes down to 368 K, the drying or moisture evaporation process is assumed to be terminated (i.e.,  $\dot{\omega}_{dry}$ ), while the re-condensation process takes place, which can be described by:  $\dot{\omega}_{re} = k_{re} G_{vap}$ . On the other hand, if drying temperature crosses the temperature boundary of 368 K, the re-condensation process is terminated (thus  $\dot{\omega}_{re} = 0$ ), while moisture evaporation initiates according to the kinetic expression  $\dot{\omega}_{dry} = k_{dry} \rho$  (here  $\rho$  is corrected or bulk density).

Chan et al.[19] quoted drying rate parameters  $A_{dry}$  ( $= 5.13 \times 10^6 s^{-1}$ ) and  $E_{dry}$  ( $= 88 \text{ kJmol}^{-1}$ ), while for re-condensation, the proportionality constant may be chosen by comparison with the measurements. Value of re-condensation factor  $k_{re}$  has been fixed at  $1.25 \text{ m}^{-1}$  following [3] whenever the temperature goes down to 368 K.

### B. Pyrolysis

Biomass pyrolysis process is a very complex, the rate of devolatilization and pyrolysis product compositions depend on temperature, heating rate, residence time and characteristics of biomass materials. In present work, the overall process of biomass pyrolysis is broken down into two modules: rate chemical kinetics and volatile product composition. The rate of

volatile release has been described by chemical kinetics of pyrolysis, while pyrolysis yields and volatile composition has been obtained simplified model as a function of bed temperature and overall biomass consumption rate. For modeling of pyrolysis process of biomass chips in fixed beds, following assumptions are invoked as:

1. Char and biomass are assumed to be non-porous.
2. The biomass shrinks on pyrolysis leaving behind solid char and ash residues.
3. Char yield during pyrolysis is independent of the pyrolysis temperature.
4. Char yields from cellulose, hemicellulose and lignin constituents of biomass have same chemical composition.
5. Char is considered to be pure carbon neglecting the presence of any other constituents like hydrogen.
6. The temperature variation within the solid particles during pyrolysis is negligible.
7. Volatile breaks up into CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, tar (heavy hydrocarbons) and light hydrocarbons.
8. Pyrolysis is assumed to be in thermally thick regime (i.e., moisture content not affect product yields).

Mathematically, pyrolysis rate can be described by system of equations or schemes of reactions basically described by chemical kinetics, heat and mass transfer. The global reaction scheme of biomass pyrolysis has been generally described using apparent kinetics [20]. In the present work, the rate of evolution of volatiles from dry biomass (db) has been described by a single pseudo-first order reaction for the sake of simplicity:

$$\text{Dry biomass} = \text{Char} + \text{Volatiles (CO, H}_2\text{, CO}_2\text{, H}_2\text{O, Methane equivalent \& tar)} \quad (8a)$$

$$dM_{vol}/dt = -k_{pyr} M_{vol} = -k_{pyr} M_{bd} Y_{vol} \quad (8b)$$

where  $k_{pyr}$  is the reaction rate of pyrolysis process,  $M_{vol}$  is the volatiles remaining in the biomass in the control volume under consideration,  $M_{db}$  is the mass of dry biomass within the control volume, while  $Y_{vol}$  is the mass fraction of volatiles remaining in the dry biomass, both of which are determined from the state of the biomass at the inlet of the control volume. Roberts [21] expression for reaction rate is used:

$$k_{pyr} = 7.0 \times 10^7 (s^{-1}) \exp(-1560/T) \quad (9)$$

The total volatiles released from the biomass in the control volume  $i$  in terms of residence time of the biomass can be written as:

$$\Delta M_{vol,i} = M_{vol,i} \left(1 - e^{-k_{pyr} \Delta t_{res}}\right) \quad (10)$$

The actual pyrolysis process of product formation is highly complex. It involves formation of more than hundred intermediate products. For describing the volatile products along with solid substrate char during slow pyrolysis process of the biomass, this research follows the modeling approach [11, 22]. Here the fuel is considered to have three main chemical constituents viz., cellulose, hemicelluloses and lignin. Their

mass fractions are related on dry, ash-free basis:

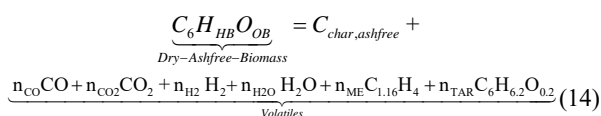
$$1 - Y_{lg} = Y_{cl} + Y_{hc} \quad (11)$$

Here  $Y$  is mass fraction of these constituents, subscripts  $cl$ ,  $hc$  and  $lg$  denote the cellulose, hemicelluloses and lignin components, respectively. These constituents become unstable and lead to thermal decomposition as and when exposed to heat. Initially, each constituent of biomass decomposes into solid substrate char and volatiles; latter the volatiles further break-up into various components including light and heavy hydrocarbons. Thus, the overall pyrolysis products can be described by combination of these products from cellulose, hemicellulose and lignin. The volatiles and char yield are sensitive to high heating rate (i.e., more than  $100^\circ\text{Cmin}^{-1}$ ) and reaction temperature. However, for the slow pyrolysis processes (nearly heating rate of  $20^\circ\text{Cmin}^{-1}$ ), the char yield is invariant with heating rates and temperature distribution [23]. Herein, the case is essentially a slow pyrolysis process, thus the char yield is assumed to be independent of temperature distribution and heating rates. If the fractions of char obtained from cellulose, hemicellulose and lignin are  $f_{char,cl}$ ,  $f_{char,hc}$  and  $f_{char,lg}$ , the total volatiles released and char yield from the thermal decomposition of unit mass of dry ash-free biomass can be expressed as:

$$Y_{char} = Y_{cl} f_{char,cl} + Y_{hc} f_{char,hc} + Y_{lg} f_{char,lg} \quad (12)$$

$$Y_{vol} = 1 - Y_{char} \quad (13)$$

Volatiles released by the primary decomposition of wood are less stable, and they break up into a large number of species including light hydrocarbon and heavy hydrocarbons or tar. Following Thunman *et al.* [9], the volatiles are considered to be CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, light hydrocarbons (ME), and heavy hydrocarbons (tar). The chemical formulas of light hydrocarbon and heavy hydrocarbon (i.e., tar) are assumed as C<sub>1.16</sub>H<sub>4</sub> and C<sub>6</sub>H<sub>6.2</sub>O<sub>0.2</sub>, respectively; while char is considered to be pure carbon. Thus, overall pyrolysis process can be expressed as:



In (14), C<sub>6</sub>H<sub>HB</sub>O<sub>OB</sub> refers to chemical formula of dry and ash-free biomass, which is obtained from cellulose, hemicellulose and lignin distribution of any type of biomass material (Table II). The char yield can also be known using Tables II and III.

Sharma *et al.* [11] fitted the mass ratios,  $\Omega_i$  (where subscript  $i$  corresponds to CO/CO<sub>2</sub>, ME/CO<sub>2</sub> and H<sub>2</sub>O/CO<sub>2</sub>) using experimental data [9, 26]. The same mass ratios are used as:

$$\Omega_{CO} = Y_{CO}/Y_{CO_2} = \exp(-1.845 + 7730.3/T - 5019898/T^2) \quad (15)$$

$$\Omega_{H_2O} = Y_{H_2O}/Y_{CO_2} = 1 \quad (16)$$

$$\Omega_{ME} = Y_{ME}/Y_{CO_2} = 5 \times 10^{-16} T^{5.06} \quad (17)$$

TABLE II  
WOOD CONSTITUENTS ON DRY BASIS [25]

Wood type	Cellulose	Hemi-cellulose	Lignin	Ash + Extractives
Softwood	0.458	0.244	0.280	0.017

TABLE III  
FRACTIONAL CHAR YIELDS FROM BIOMASS CONSTITUENTS

Constituents	Cellulose	Hemi-cellulose	Lignin	Ref.
Chemical Formula	$C_6H_{10}O_5$	$C_6H_{10}O_5$	$C_9H_{7.95}O_{2.4}(OCH_3)_{0.92}$	[10]
Char yield in fraction	0.05	0.10	0.55	[24]

The elemental balances followed by above correlations are used to obtain volatile product composition in terms of known temperature. As temperature approaches to the range of 800 K – 1000 K for different biomass substrates, the tar content in the volatiles decreases and approaches to zero, (16) is discarded and the remaining equations are solved to obtain composition.

### III. RESULTS AND DISCUSSIONS

The above formulation of biomass drying, and pyrolysis is implemented to a testing gasifier bed maintaining at isothermal temperature. Predictions are tested for qualitative trends. Simulations are also performed to study the effects of isothermal temperature conditions and zone length or residence time on volatile released profile, volatile distribution into CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, methane equivalent, tar & char is studied.

#### A. Drying

Biomass drying formulation presented above can be used to predict the moisture loss profile along the testing bed for given inputs: initial moisture content, bed temperature, test bed length or residence time, particle size and relative humidity of air. The biomass flow rate, average biomass particle half-thickness, and diameter and length of testing zone have been fixed at typical baseline values of 9 gs<sup>-1</sup>, 2 cm, 25 cm and 50 cm, respectively. In absence of suitable experimental data, the predictions are compared reasonable agreement against chemical kinetic model [19] for testing zone in gasifier maintaining at three isothermal temperature values (i.e., 350, 400 and 450 K) as shown in Fig. 1.

A minor deviation may be observed at low temperatures (less than re-condensation temperature, i.e. 368K); it is due to that Chan model has been accounted for the effect of re-condensation of water vapour below re-condensation temperature. After establishing the validity of various assumptions, the proposed drying module is employed to examine the effect of isothermal temperature, particle size, initial moisture content in biomass and relative humidity of surrounding medium on moisture loss profile.

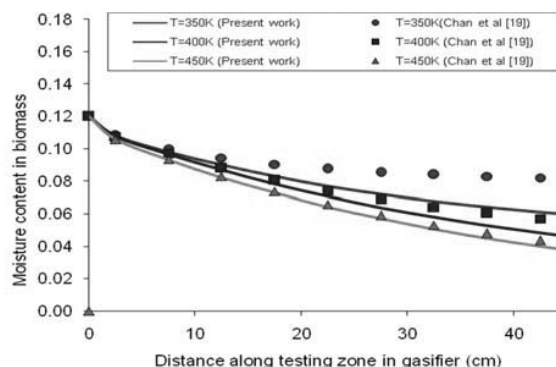


Fig. 1 Comparing predictions of drying module with Chan kinetic model

The moisture content of biomass, particle size, isothermal temperature, relative humidity in air have been varied between 0-20%, 10-40 cm, 350-550K, and 10-90% respectively. With above base values of biomass flow rate, average biomass particle half-thickness, and diameter and length of testing zone, and after excluding the thermal decomposition of biomass particles at higher temperatures, simulations are performed to predict moisture loss distribution trends in testing bed for different temperatures, particle size, the relative humidity of incoming air as shown in Figs. 2-5.

Fig. 2 depicts the patterns of moisture loss profile along the testing bed for five typical isothermal temperature conditions i.e., 350, 400, 450, 500 and 550 K. Trends revealed faster drying with higher isothermal temperature conditions along the testing bed, which can be expected. In order to investigate the effect of particle size on moisture loss profile; four different particle sizes (i.e. 10, 20, 30 and 40 mm) are considered; their influence is shown in Fig. 3. As expected, the trends indicate faster biomass drying with decrease in biomass particle diameter. The influence of relative humidity of atmospheric air on biomass drying is plotted in Fig. 4. The biomass drying is found much faster at low humidity levels of the air.

#### B. Pyrolysis of Dry Wood

Well tested product composition model of Sharma et al [11] for slow biomass pyrolysis in conjunction with single pseudo-first order devolatilization rate model is employed to describe thermal decomposition of dry wood particles in testing zone of a gasifier. Model predicts the pyrolytic yields viz., char, tar and volatiles; devolatilization rate and volatile composition in terms of bed characteristics (i.e., gasifier geometry, residence time, etc.). The specifications of chemical formulas of the char and tar, bed temperature, chemical formula of cellulose, hemicellulose and lignin, as supplied in Table II-III, will be required as input information.

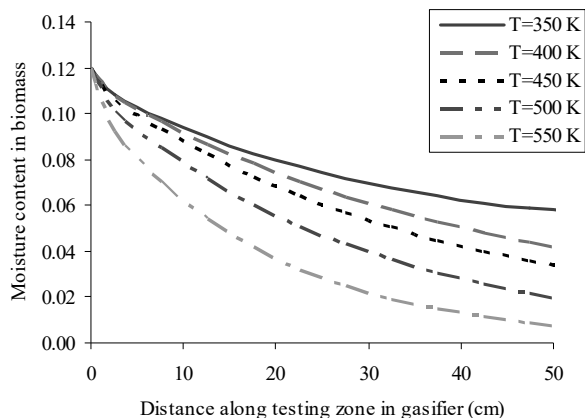


Fig. 2 Effect of isothermal bed temperature on moisture loss profiles

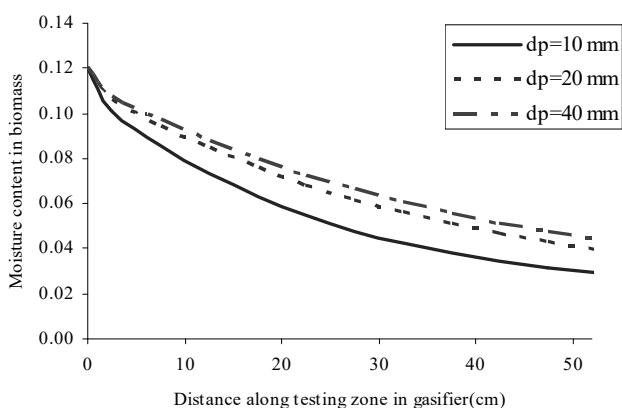


Fig. 3 Influence of biomass particle size on moisture loss profile, testing bed at 400 K

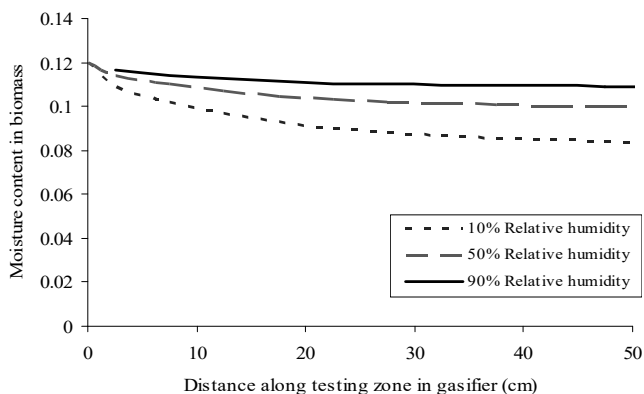


Fig. 4 Influence of relative humidity on moisture loss profile, testing bed at 325 K

For the present analysis, dry biomass flow rate, length and diameter of testing zone are fixed at typical baseline values of 9 g/s, 50 cm and 25 cm, respectively. In order to emphasize the volatile releasing process, dry biomass is used to avoid the role of moisture evaporation and restrict airflow through the testing bed by forcing equivalence ratio (EQ) to zero. With these base values and imposed constraints, the simulation was performed

to predict char, ash and volatile release rate and flow rates of volatile products as shown in Figs. 5-7.

For investigating the influence of isothermal temperatures on volatile released profile, the testing zone is maintained at four typical isothermal temperature specifications i.e., 550 K, 600 K, 650 K and 700 K to compare the effect on volatile release profile (cf. Fig. 5). Simulations show that as isothermal temperature increases, the volatile driven off more quickly within a short length, as expected. Fig. 6 gives the distribution of char, ash and volatiles across the testing bed maintaining the temperature of 675 K. The results shows that fast release of pyrolysis products (i.e. char and volatiles) can be observed initially from the biomass particles, thereafter, trends become almost independent of bed length or residence time as all biomass gets consumed completely (Fig. 6). Fig. 7 shows the distribution of volatile products into CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, methane equivalent and tar along the testing bed. These trends are observed similar to Fig. 6. Distributions of CO<sub>2</sub>, H<sub>2</sub>O and tar are found on higher side, while methane equivalent and hydrogen component in volatiles are observed to be on lower side when biomass gets consumed completely.

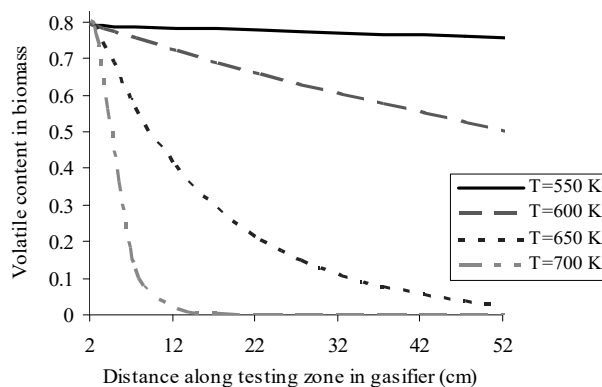


Fig. 5 Influence of isothermal bed temperature in testing zone on volatile released profile, dry biomass

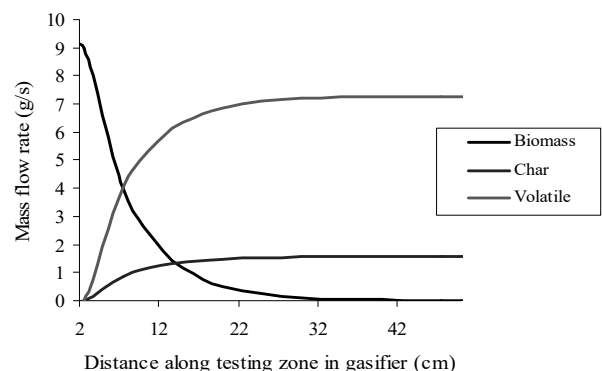


Fig. 6 Distribution of char/volatiles during thermal decomposition of biomass, testing bed temperature: 675 K, dry biomass

### C. Pyrolysis of Moist Wood

The process of drying and pyrolysis of moist wood particle in gasifier bed depends on heating rates, temperature, types of biomass materials, particle size, and initial moisture content.

For fuel bed constituted by thermally thin particles at slow heating rates, these processes take place sequentially [12]. To understand the biomass drying and pyrolysis process of moist and thermally thick wood particles, the equations representing the drying and pyrolysis processes are integrated and implemented to a 50 cm long testing bed. This model is used to predict moisture evaporation, pyrolytic yields (char, tar and volatiles), devolatilization rate and volatile composition as function of bed characteristics (bed porosity, gasifier geometry and residence time), bed temperature and biomass consumption rate.

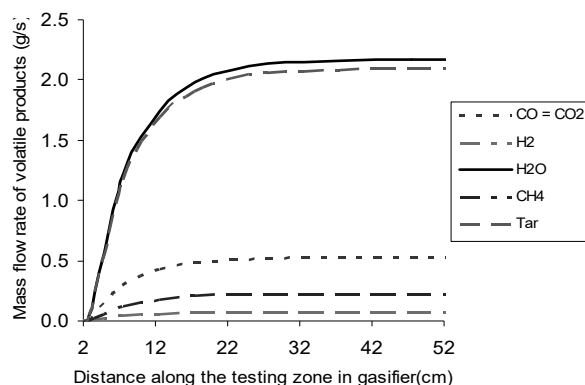


Fig. 7 Distribution of volatiles products viz., CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, Methane equivalent (ME) and tar along testing bed

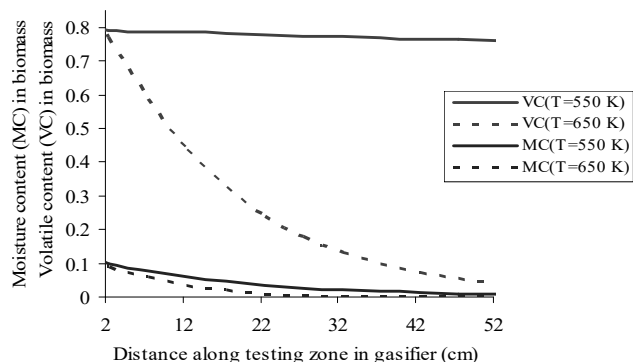


Fig. 8 Influence of isothermal temperatures through the testing bed on moisture loss and volatile release profile, wet biomass

The inputs to the model are same as described in previous case, except the dry biomass feedstock is replaced with moist biomass having initial moisture content of 0, 10 and 20%, respectively. The air inflow through the testing zone is controlled by varying the equivalence ratio from 0.05 to 0.4 (with baseline value of 0.37). With this information, the simulations are performed to identify the role of initial moisture content, isothermal temperature and relative humidity of ambient air on moisture loss profile, char and volatiles release profile, mass flow rate of volatile species as shown in Figs. 8 and 9.

The influence of initial moisture content in biomass particles on volatile release profile at two different isothermal temperatures (i.e. 550 K and 650 K) are shown in Fig. 8. The

volatile releasing process at low temperature (i.e., 550 K) is observed to be extremely slow, while at higher temperatures (i.e. 650 K), both the volatile releasing and moisture evaporation rates are found to be very high in contrast to moisture loss profile.

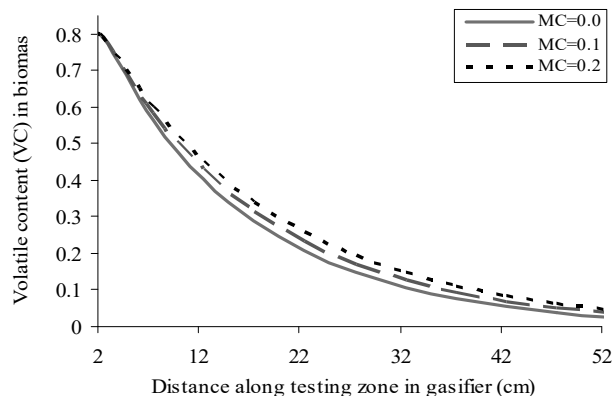


Fig. 9 Influence of initial moisture content on volatile released profile, bed maintained at isothermal temperature 675 K

Fig. 9 includes the role of initial moisture content on volatile released profiles along the testing zone at isothermal bed temperature of 675 K. Volatile released profile decreases with increasing moisture content in biomass particles.

#### IV. CONCLUSIONS

Drying and pyrolysis module for moist biomass particles in packed bed of the gasifiers is presented, here biomass drying is described by the analytical solution of 1-dimensional mass diffusion and equilibrium moisture content of biomass is derived in terms of temperature and relative humidity of surrounding air. Following conclusions are derived out of present work:

1. Predictions of drying module agree fairly at wide temperature range with chemical kinetics scheme from literature.
2. A high temperature gasifier bed constituted from relatively smaller particles with larger airflow rate tends faster particles drying.
3. At high temperatures volatile releases more quickly within a shorter length.
4. Predictions for moisture loss profile and volatile release profile are found to be sensitive to the temperatures, while role of initial moisture content in biomass particle bed is found to be less sensitive to volatile release profile.

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