

# DRYING AND DEVOLATILIZATION OF A WET BIOMASS PARTICLE UNDER FLUIDIZED BED COMBUSTION CONDITIONS

G. I. PALCHONOK<sup>1</sup>, V. I. DIKALENKO<sup>1</sup>, L. K. STANCHITS<sup>1</sup>, V. A. BORODULYA<sup>1</sup>,  
J. WERTHER<sup>2</sup>, B. LECKNER<sup>3</sup>

<sup>1</sup>A.V.Luikov Heat and Mass Transfer Institute, Academy of Sciences of Belarus, Minsk, Belarus

<sup>2</sup>Technical University of Hamburg-Harburg, Hamburg, Germany

<sup>3</sup>Chalmers University of Technology, Geteborg, Sweden

Biomass and organic waste are becoming increasingly interesting for energy production. Thermal conversion of these renewable fuels reduces CO<sub>2</sub> and sulfur emissions and offers an alternative to waste disposal. Fluidized bed combustion (FBC) is a widely available method for this purpose. Combustion of a highly moist biofuel is of special interest because it may prevent an abrupt release of volatiles near the feeding point, thus enhancing the uniformity of the distribution of combustibles over the fluidized bed cross-section. This will facilitate the completeness of combustion and suppresses formation of hydrocarbon pollutants and NO<sub>x</sub>. Drying and devolatilization of a moist biomass particle are the main stages of combustion, since the fixed carbon content is only around 10 % of the particle mass in this case. The aim of this work is to further investigate combustion mechanisms relevant for highly wet biomass and waste particles under FBC conditions and to establish a simplified model for generalizing experimental data.

Measurements of the temporal change in mass and temperature of a single burning particle, as well as visual observations of flame combustion of volatiles and glowing char combustion have been carried out in a 55 mm fluidized bed reactor at A.V. Luikov Institute. The bed material was silica sand of a Sauter mean diameter 0.57 mm and a density of 2540 kg/m<sup>3</sup>. The static bed height was 75 mm. The fluidizing gas was air with an oxygen content of 21% and the superficial velocity was kept at around 0.5 m/s. The bed temperature was 973 to 1123 1C. The volatile flame ignition and extinction times, the latter being treated as the volatiles release time, were registered. A fuel particle temperature was measured with embedded K-type thermocouples. Another set of measurements was carried out in a 100 mm fluidized bed reactor at the Technical University Hamburg-Harburg under similar conditions. Drying, volatile and char combustion of a single burning particle were monitored by means of time-resolved profiles of gas concentrations measured downstream of the cyclone

Spherical particles (Ø=3-35 mm) of wood (pine and birch), hydrolytic lignin, industrial sewage sludge (sludge-M), and municipal sewage sludge (sludge-H) were used as model fuels. The lignin, a by-product of ethanol production from wood, and the sludge-M, a waste of leather processing, were obtained from factories situated near Minsk. The digested sludge-H was obtained from Hamburg's central waste-water treatment plant. Table 1 shows the proximate fuel analysis.

Table 1. Proximate fuel analysis, wt.-% as tired

	Wood	Lignin	Sludge-M	Sludge-H
Moisture, W	40.0	60.1	75.0	76.0
Volatile matter, V	50.2	27.5	12.0	12.4

Fixed carbon, C	8.8	11.1	4.2	1.1
Ash, A	1.0	1.3	8.8	10.5

A model of coupled drying and devolatilization was developed based on the following assumptions: An isotropic and homogeneous fuel particle of a constant size is considered. All the moisture content is free water. The drying occurs at the receding surface of the wet core, the process rate being heat-transfer controlled. An abrupt pyrolysis occurs when the dry shell locally reaches a characteristic pyrolysis temperature,  $T_p$ . The latter corresponds to the higher limit of the temperature range of thermal destruction of biomass. The temperature profiles in the outer char shell and in the intermediate dry layer are those of a steady state condition. The wet/dry interface temperature,  $T_{wc}$ , remains constant at the saturation temperature. For simplicity, the initial temperature of the particle is equal to  $T_{wc}$ . The water vapor and pyrolysis gases do not affect the heat transfer because of the existence of cracks and no mass transfer effect is concerned for the same reason.

Table 2. The model solutions

	Sphere	Cylinder	Slab
Geometry factor, b	2	1	0
<b>One-layer model</b> , $\lambda_{ch} = \lambda_d = \lambda_{eff}$			
Temperature profile, $\Theta$	$\frac{R - R_{wc}}{R(1 - B_1 R_{wc})}$	$\frac{\ln(R_{wc}/R)}{\ln R_{wc} - 1/Bi}$	$\frac{R - R_{wc}}{1/Bi + (1 - R_{wc})}$
Temporal evolution of the wet/dry interface, $\tau = t/t_0$	$\frac{1}{2}(1 - R_{wc}^2) - \frac{B_1}{3}(1 - R_{wc}^3)$	$\frac{Bi+2}{4Bi}(1 - R_{wc}^2) + \frac{1}{2}R_{wc}^2 \ln R_{wc}$	$B_2(1 - R_{wc}) - \frac{1}{2}(1 - R_{wc}^2)$
Drying time, $t_{w,c}$		$t_0 \frac{Bi + 2}{(2 + 2b)Bi}$	
Pyrolysis radius, $R_p = \text{Min}(1, R_p)$	$\frac{R_{wc}}{1 - \Theta_p(1 - B_1 R_{wc})}$	$R_{wc} \exp\left[\Theta_p \left(\frac{1}{Bi} - \ln R_{wc}\right)\right]$	$R_{wc}(1 - \Theta_p) + B_2 \Theta_p$
<b>Two-layer model</b> , $\lambda_{ch} \neq \lambda_d$			
Drying time, $t_{w,c}$		$t_{p,o} + t'_{w,c}$	
Wet/dry radius at the beginning of pyrolysis, $R_{wc,o}$	$\frac{1 - \Theta_p}{1 - B_{1d}}$	$\exp\left(\frac{\Theta_p}{Bi_d(\Theta_p - 1)}\right)$	$\frac{1 - B_{2,d}\Theta_p}{1 - \Theta_p}$
Pyrolysis starting time, $t_{p,o}$	$\frac{1}{2}(1 - R_{wc,o}^2) - \frac{B_{1d}}{3}(1 - R_{wc,o}^3)$	$\frac{Bi_d + 2}{4Bi_d}(1 - R_{wc,o}^2) + \frac{1}{2}R_{wc,o}^2 \ln R_{wc,o}$	$B_{2,d}(1 - R_{wc,o}) - \frac{1}{2}(1 - R_{wc,o}^2)$
Temporal evolution of the wet/dry interface, $\tau' = t'/t'_o$	$\frac{1}{2(1+\Lambda)\Theta_p} \left( \frac{1}{2}(1 - R'^2_{wc}) - \frac{1}{3}B_{1, ch} R_{wc,o} (1 - R'^3_{wc}) \right)$	$\frac{1}{(1+\Lambda)\Theta_p} \left[ \left( \frac{Bi+2}{4Bi} - \frac{\ln R_{wc,o}}{2} \right) (1 - R'^2_{wc}) + \frac{1}{2}R'^2_{wc} \ln R'_{wc} \right]$	$\frac{Bi_{ch} + 1}{Bi_{ch}(1+\Lambda)R_{wc,o}} (1 - R'_{wc}) - \frac{1}{2(1+\Lambda)} (1 - R_{wc}^2)$
$\tau'_{w,c} = t'_{w,c}/t'_o$	$\frac{1}{(1+\Lambda)\Theta_p} \left( \frac{1}{2} - \frac{B_{1, ch} R_{wc,o}}{3} \right)$	$\frac{1}{(1+\Lambda)\Theta_p} \left( \frac{Bi_{ch} + 2}{4Bi_{ch}} - \frac{1}{2} \ln R_{wc,o} \right)$	$\frac{Bi_{ch}(2 - R_{wc,o}) + 2}{2Bi_{ch}(1+\Lambda)\Theta_p R_{wc,o}}$
Pyrolysis radius, $R_p = \text{Min}(1, R_p)$	$\frac{R_{wc}(1+\Lambda)}{\Lambda + B_{1, ch} R_w}$	$\exp\left(\frac{1/Bi_{ch} + \Lambda \ln R_{wc}}{1+\Lambda}\right)$	$\frac{B_{2, ch} + \Lambda R_{wc}}{1+\Lambda}$
<b>Notations</b>	$t_0 = \frac{q\rho_0 W_0 r_0^2}{\lambda_d (T_b - T_{wc})}$ ; $t'_o = t_0 R_{wc,o}^2$ ; $R' = R \cdot R_{wc,o}$ ; $B_1 = \frac{Bi-1}{Bi}$ ; $B_2 = \frac{Bi+1}{Bi}$		

Provided that the thermal properties are constant, analytical solutions were obtained, see Table 2, for two cases: (i) one-layer shell, with no difference between the char and biomass properties; and (ii) two-layer shell. The overall heat transfer coefficient to/from a fuel particle submersed in a fluidized bed was calculated as a sum of a convective, Leckner et al. (1992), and a radiative constituents. The latter was estimated with the emissivity being put to 0.8 for both the fuel particle and the fluidized bed.

Thermal conductivities of virgin dry biomass,  $\lambda_d$ , and char  $\lambda_{ch}$ , are defined in the model as average values over the temperature range considered. The measured temperature in the center of the spherical particles revealed a plateau around 373 to 393 K, corresponding to the evaporation temperature at the dry-wet interface. The value of  $T_{wc}= 373$  K. and the pyrolysis temperature  $T_p= 673$  K are input to the calculations. Provided that the external temperature of the char layer quickly reaches a temperature close to the bed temperature, which agrees with measurements and theory for quite large Biot numbers, the reference temperature can be estimated  $T_{ch}=0.5(T_p + T_b)$  for char and  $T_d=0.5(T_{wc} + T_p)=523$  K for wood. Usually, the bed temperature in a combustor is around 1073 K which leads to  $T_{ch}=873$  K. At such a temperature a radiative thermal conductivity,  $\lambda_r$ , can provide an essential input. Accounting for a high porosity of char, around 0.9 for wood, a model of Pavlyukevich (1990) for radiation in a highly porous material can be used to estimate  $\lambda$ . An estimate for wood-char under the above conditions yields a value of around 0.04 W/(mK). This should be added to the thermal conductivity of wood-char for same conditions, which amounts to around 0.07 W/(mK), Fredlund (1990). An analogous estimate of the radiative conductivity for virgin dry wood was negligibly small because of the low reference temperature as compared to the thermal conductivity, which was around 0.14 W/(mK) in the radial direction. The thermal conductivity of dry wood and wood-char recommended by Fredlund (1990), based on MacLean's empirical equation, were used in the model calculations. For other fuels no data are available, and the thermal conductivity was determined by fitting.

The conversion extent of volatiles,  $X_v$ , at the moment when the drying is practically finished,  $X_w=99\%$ , is shown versus the Biot number in Fig.1 for a sphere, a cylinder, and a slab.

The calculations were made with the one-layer model. It follows from Fig. 1 that the model is not applicable at low Biot numbers,  $Bi < 0.5$  for a sphere and cylinder and  $Bi < 1$  for a slab. This is because of a uniform intra-particle temperature at low Bi, which prevents the start of the pyrolysis until the moisture has gone. At  $Bi > 10$ , which is typical at FBC conditions,  $X$ , becomes practically independent on Biot number and reaches nearly 100% for a sphere and a cylinder and above 50% for a slab. The conclusion can be drawn that the end of pyrolysis of a sphere and a cylinder coincides with the end of drying. This conclusion can be spread on finite 3-dimensional particles shaped as combinations of infinite cylinders and/or slabs.

The mass loss history of spherical particles of 50%-moist wood and sludge-H is shown in Fig.2. The experimental data for wood are compared with calculated results using the two-layer model in Fig.2a. the thermal conductivity being chosen to 0.14 W/(mK) for dry wood and 0.11 W/(mK) for wood-char. The latter values correspond to literature recommendations concerning the radial or tangential thermal conductivity of wood. The good agreement between the measured and the calculated data implies that the counter-flow of the gaseous products along the fibers compensates the higher thermal conductivity in this direction, while the rate of the process was limited by the transversal

conduction of the heat. For the sludge, the thermal conductivity was fitted.  $\lambda_d=\lambda_{ch}=0.25$  W/(mK) gave in the best fit, see Fig.2b.

A comparison between model calculations (line) and experimental volatile release time is shown versus the initial particle diameter in Fig.3 for the spherical particles of the lignin, 40%-moist wood, and sludge-M. The best-fit thermal conductivity was  $\lambda_d=\lambda_{ch}=0.2$  W/(mK) for the lignin and the sludge, whereas for the wood the same values as in Fig. 2 were used.

Simultaneously measured temperature histories in the center of cylindrical particles and in the center of the end surface clearly showed that the ends had a temperature close to  $T_{wc}$  for quite a long period of time. The explanation may be that free moisture is transferred along the fibers to the end surface faster than the drying front penetrates into the particle. In such a case, an initial period of drying at the surface normal to the fiber axis has to be distinguished. Thus, a simplified model was used to describe drying and pyrolysis of cylindrical wood particles with  $D/L=1$ ,  $D=30$  mm. It was assumed that only surface drying occurs at the ends unless the average drying reaches a concentration of  $W^*$ . Subsequently, the drying time was calculated for an infinite cylinder of a diameter  $D$  and an infinite slab of a thickness  $L$  according to the two-layer model. The shortest of the two estimated times was regarded as the model output. The results are shown in Fig.4 as volatile release time versus cylinder shape factor, defined as the ratio of the surface area of a volume equivalent sphere to the cylinder surface area. The least discrepancy (around 30%) between the measurements and calculations was obtained for  $W^*=0.4$  and the same thermal conductivity for both axial and radial directions, 0.14 W/(mK) of dry wood and 0.11 W/(mK) of wood-char.

## Conclusion

New data are obtained on the mechanisms of drying and devolatilization of wet biomass and waste fuels under FBC conditions. A mathematical model is established of coupled drying and pyrolysis of moist biomass particles of different geometrical forms. The model gives a reasonably good representation of the measurements, provided that the thermal conductivity of the particle is used as a fitting parameter. The effective conductivities found for homogeneous lignin and sewage sludges are close to each other. The description of the performance of anisotropic wood particles uses the same thermal conductivity for both axial and transversal directions.

## Nomenclature

$b$  - geometry factor,  $Bi$  - Biot number,  $D$  - diameter of cylinder,  $L$  - height of cylinder,  $q$  - latent heat of evaporation,  $r$  - coordinate,  $r_0$  - initial particle radius,  $R=r/r_0$ ,  $T$  - temperature,  $T_a$  - time-average surface temperature of a fuel particle,  $T_p$  - upper limit of the pyrolysis temperature range,  $T_{wc}$  - temperature at the wet core surface,  $t$  - time,  $t_0$ ,  $t'_0$  - characteristic drying time before/after the start of pyrolysis,  $X$  - conversion extent, (mass loss)/(initial mass),  $W$  - moisture content, kg/(kg wet biomass),  $W^*$  - critical moisture content,  $\Lambda = \lambda_{ch} (T_b - T_p) / \lambda_d (T_p - T_{wc})$ ,  $\lambda$  - thermal conductivity,  $\Theta = (T - T_{wc}) / (T_b - T_{wc})$ ,  $\Theta_{ch} = (T - T_p) / (T_b - T_p)$ ,  $\Theta_d = (T - T_{wc}) / (T_p - T_{wc})$ ,  $\rho$  - density,  $\tau = t/t_0$ . Subscripts: b - bed, ch - char, d - dry biomass, e - end, o - initial; beginning of the pyrolysis, p - pyrolysis, w - drying, wc - wet core.

## References

1. B.Fredlund. *Calculations of the Fire Resistance of Wood Based Boards and Wall constructions*, Lund University, Sweden (1990)

2. B. Leckner, G.I. Palchonok, B.-A. Andersson, *Representation of Heat and Mass Transfer of Active Particles*, IEA-FBC Mathematical Modeling Meeting, International Energy Agency, Turku (1992)
3. N.V. Pavlyukevich, *J. Eng. Phys.*, 59, 1284-1286 (1990)

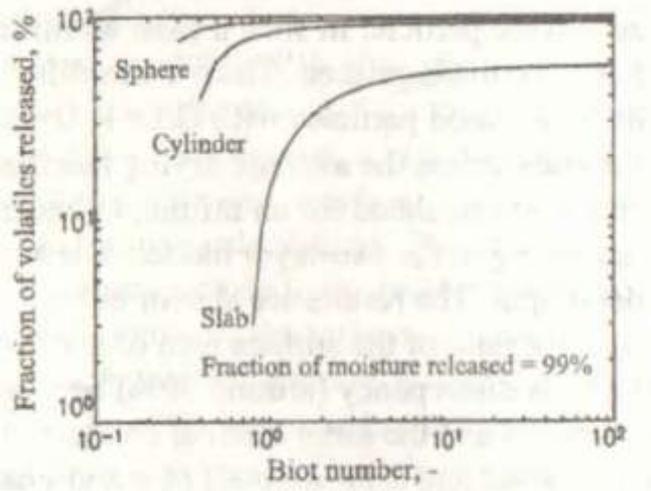


Fig. 1. Calculated fraction of volatiles released at the end of the drying period versus Biot number.

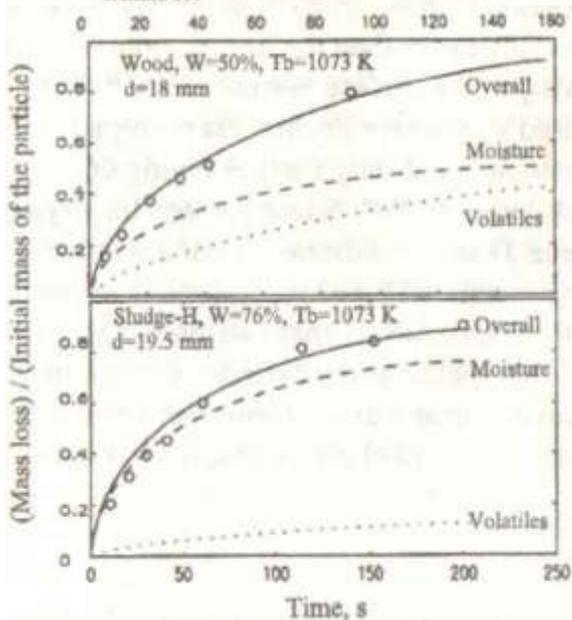


Fig. 2. Mass loss histories of spherical wood (a) and sludge-H (b) particles (circles are measured values and lines are calculated).

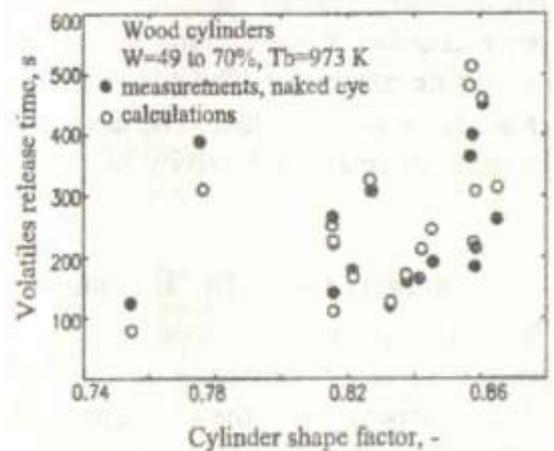
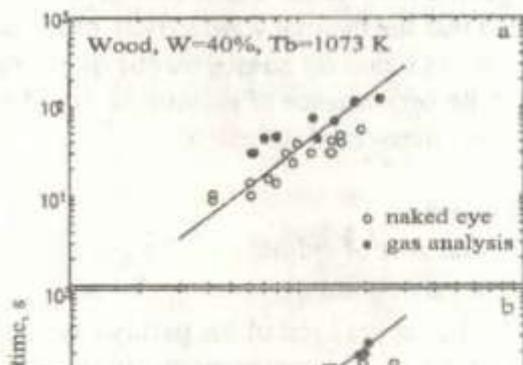


Fig. 3. Comparison between experimental (symbols) and calculated (line) volatiles release times of spherical particles of wood (a), lignin (b) and sludge-M (c)

Fig. 4. Experimental and calculated volatiles release times of wood cylinders versus shape factor