

UNSTEADY-STATE PROBLEM OF HEATING, DRYING AND DEVOLATILIZATION OF A BIOFUEL PARTICLE IN A FLUIDIZED BED

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Combustion of solid and paste-like particles of biofuel or fuel wastes in a fluidized bed is distinguished by complex aerodynamic and thermal interaction with inert dispersed material and oxidant. In addition, each fuel particle undergoes a series of consequent physico-chemical changes (that can overlap in time): heating, drying and further heating, yield and combustion of volatile matter (as a rule, when mixed with water vapor), combustion of char carbon. The objective of this study is to consider the problems on numerical modeling of heating dynamics of moist biofuel particles with regard to phase changes in them.

The problem of numerical modeling of the heating dynamics of a spherical particle with regard to phase transformations in it is governed by the unsteady-state heat conduction equation with a nonlinear boundary condition on its surface and with a Stefan condition on the phase change boundary at a given temperature. In this case, differences in thermal properties of moist and dry biofuel particles partially exposed to pyrolysis after phase change (moisture evaporation in a solid skeleton) are taken into account. In such a statement, the problem is solved with the intention of quantitative comparison with the results obtained in a quasi-steady statement [1].

In time the problem is divided into three stages:

- a) heating of a wet biofuel particle from an initial temperature T_0 to a phase-change temperature T_w (evaporation temperature) on its surface;
- b) further heating of the particle with moisture evaporation at the surface of the wet core moving deep into it;
- c) heating of a particle after the completion drying process (radiation of burning volatile matter from flame can be further allowed for)

1. The first heating stage is described by the unsteady-state heat conduction equation:

$$\rho_{po} c_p \frac{\partial T}{\partial t} = -\operatorname{div} \mathbf{q} .$$

(1)

$$\mathbf{q} = -\lambda_{wet} \frac{\partial T}{\partial r} .$$

(2)

under the following initial and boundary conditions:

$$T(r,t) = T_0; \quad t = 0;$$

(3)

$$\frac{\partial T}{\partial r} = 0, \quad r = 0;$$

(4)

$$q_s = q(r = R_0, t) = \alpha(T_b - T_s) + \varepsilon c_0(T_b^4 - T_s^4), \quad r = R_0.$$

(5)

2. Active particle drying is started when the phase-change temperature (water boiling temperature $T_w = 373\text{K}$.) is reached at the particle surface at moment τ^* . In this case the heating dynamics of a wet biofuel particle are governed by a system of conjugated equations of heat conduction in the wet core ($0 \leq r \leq r_w$), that coincides with system (1)-(2) with boundary condition (4) and with the Stefan condition at the wet core surface, and that in a dried sphere layer, with system (6)-(7) over the range ($r_w \leq r \leq R_o$):

$$\rho_{dry} c_{dry} \frac{\partial T}{\partial t} = -\text{div } \mathbf{q}$$

(6)

$$\mathbf{q} = -\lambda_{dry} \frac{\partial T}{\partial r}$$

(7)

where the subscript "dry" denotes the parameter of dry substance partially exposed to pyrolysis. Problem (6)-(7) uses boundary condition (5). Equations (1)-(2) and (6)-(7) are connected by the Stefan condition (8) at the wet core radius $r = r_w$:

$$q_{dry} - q_{wet} = \lambda_{wet} \frac{\partial T}{\partial r} \Big|_{r=r_w-\delta} - \lambda_{dry} \frac{\partial T}{\partial r} \Big|_{r=r_w+\delta} = \rho_{po} r^* W^p \frac{dr_w}{dt}$$

(8)

Here $r^* = 2256 \text{ kJ/kg}$ is specific heat evaporation of water; W^p is the moisture content (as fired). Expression (8) results from the condition of thermal energy conservation at phase-change and it reflects the fact that the difference of heat fluxes from the phase boundary in dry and moist substance is spent for moisture evaporation.

3. At the third stage, when the wet core surface reaches the sphere center, its further heating is described by equations (6)-(7) with boundary conditions (4)-(5). Thermal characteristics of biofuel are assumed constant in moist and dry substances and refer to mean temperatures in moist and dry regions for particle drying time. Thermal conductivity of dry substance is determined by the empirical formulas for porous media [2] and experimentally for moist particles since handbooks practically contain no necessary data for test materials other than wood. It has appeared that the thermal conductivity of lignin, sludge-H, and wood increases with their moisture content but does not exceed 1 W/m K , Fig. 1. Steady and unsteady-state methods have been used for determination

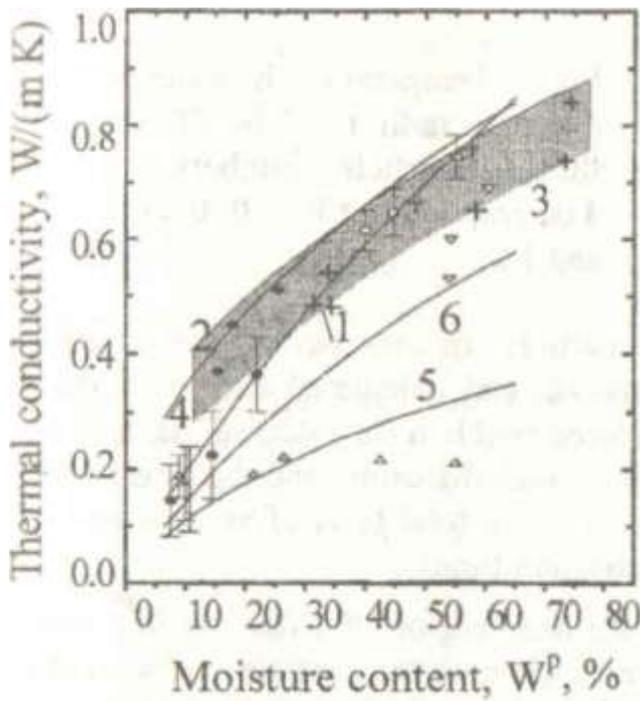


Fig.1. Thermal conductivity of different biofuels measured by the unsteady method of regular thermal regime (at heating in fluidized bed (U1) and in water (U2)) and by the steady-state method (S): •, □, lignin, U1 and U2, respectively; 1, best fit curve; ♦, +, sludge-H, U1 and U2, respectively; 2,3 boundaries of the domain for sludge-H thermal conductivity; Δ, wood (U1), ▽ - (U2), ×, (S), respectively; I, tabular data for air-dry wood [5]; 4, ($\lambda_{||}$) and 5, (λ_{\perp}), McLean's correlations [6] for axial and transversal directions, respectively; 6, Shubin's correlation for wood [7].

of the thermal conductivity of the said biofuels. The sweep method (I.M. Gelfand and O. V.Lokutsievsky's algorithm [3]) with iterations of the Stefan condition at the phase boundary is used to numerically solve the stated problem. Table 1 shows proximate analysis of used fuels Hydrolytic lignin with addition of lime is applied in the experiments.

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

Biofuel type	Parameters			
	Moisture, W^P	Volatile matter, V^P	Fixed carbon, C^P	Ash, A^P
Wood	40.0	50.2	11.1	1.0
Lignin	64.5	21.3	7.7	6.5
Sludge-H	76.0	12.4	1.1	10.5

Fig. 2 and 3 are plots of the typical calculated results for temperature distribution in a heated sludge-H particle with water and volatile matter yield.

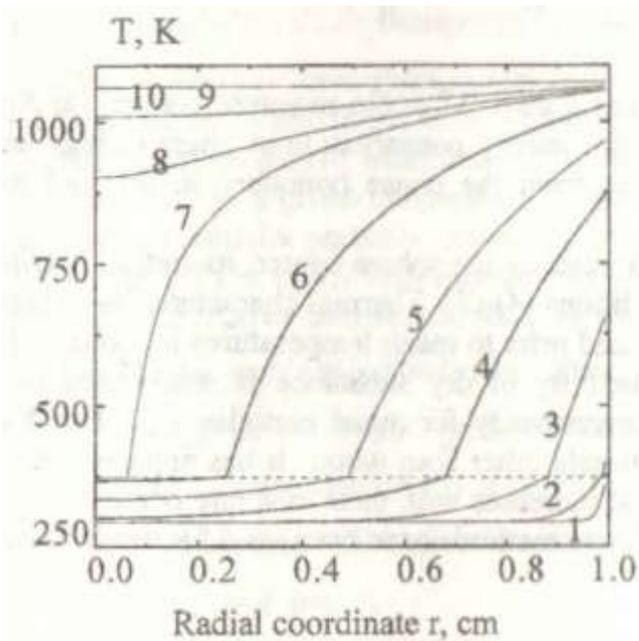


Fig. 2. Temperature profiles in the 20mm Sludge-H particle at different time moments. Numbers 1 to 10 correspond to $t = 0.1, 1.1, 10, 30, 50, 70, 79, 80, 81$ and 84 s.

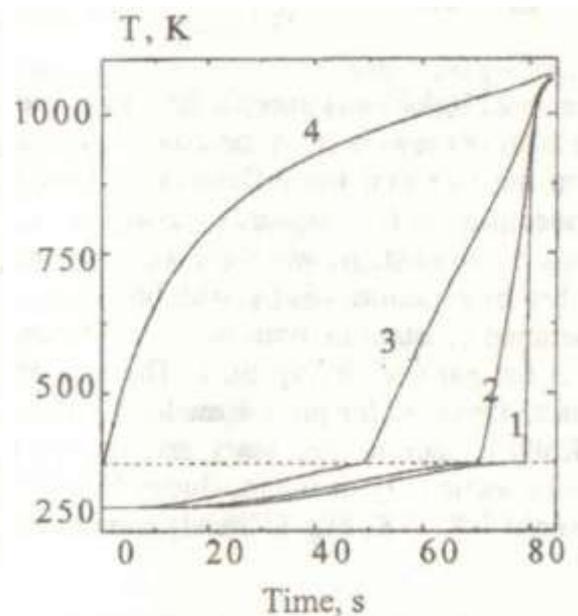


Fig.3. Temperature histories at different radii r , of the 20 mm Sludge-H particle. Numbers 1 to 4 correspond to $r/R_0 = 0; 0.25; 0.5$ and 1.0 .

Fig. 4 shows mass losses of lignin and wood particles in time when burnt in a fluidized bed. These cases also reflect comparison of experimental and calculated data with the results obtained in the quasi-steady statement [1] of the considered problem (in calculations, it is assumed that mass transfer of volatile matter in a particle occurs through diffusion, and the time dependence of volatile matter yield can be described according to [4]. The total time of volatile matter yield was determined experimentally through the flame combustion time).

Obtained results testify that vapor yield from the deep region of a fuel particle is retarded by volatile matter actively formed in layers that are more close to the particle surface and have a higher temperature. Therefore, the assumption of simultaneous yield of volatile matter and water vapor [1] better corresponds to the real process of mass loss by a moist fuel particle when burnt in a fluidized bed than in the case when this process with moisture and volatile matter yield displaced in time is considered.

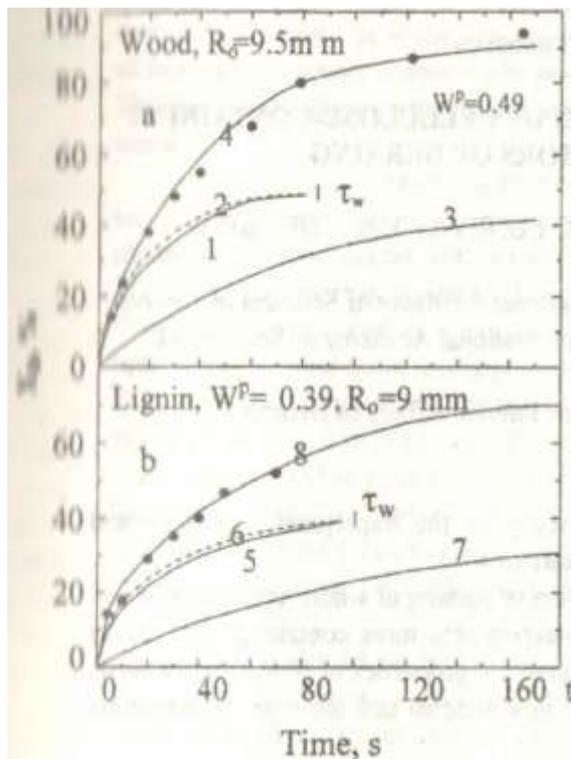


Fig. 4. Comparison of experimental and calculated mass loss values of wood (a) and lignin (b) particles (dots are measured values and lines are the calculated ones), a) wood: 1, calculated curve from problem (1) - (8); 2, from quasi-steady problem [1]; 3, calculated release of volatile matter [4], 4, overall yield of water vapor and volatile matter; b) lignin: 5, calculated data from unsteady-state problem (1) - (8); 6, from quasi-steady problem [1]; 7, calculated yield of volatiles from [4]; 8, overall yield of water vapor and volatile matter

Nomenclature

c_0 , Stefan-Boltzman constant, $J/(m^2 s K^4)$; T , temperature, K; R_0 , initial particle radius, m; T_w , temperature at the wet core surface, K; r , coordinate, m; r_w , wet core radius, m; λ , thermal conductivity, $W/(m K)$; ρ_{po} , initial particle density, kg/m^3 ; q , heat flux, W/m^2 ; α , heat transfer coefficient of a fuel particle, $W/(m^2 K)$; ϵ , effective emissivity of the bed fuel particle system; C_p , specific heat capacity, $J/(kg K)$; t , time, s; W^p , moisture content (as fired); X_B , (mass loss)/ (Initial mass of the fuel particle). Subscripts: b, bed; o, initials; s, surface; wet, wet core; dry, fall to dry matter.

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