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APPENDIX

Appendix A: Calculation in mass and energy balances study

1. Higher heating value of raw and torrefied biomass

The percentages of carbon (C), hydrogen (H), oxygen (O), sulfur (S), and nitrogen (N) were used in the calorific value calculation. An ordinary least squares regression (OLS) (Eq. (1)) and a partial least squares regression (PLS) (Eq. (2)) were used in this calculation.

$$HHV\ (OLS) = 1.87C^2 - 144C - 2802H + 63.8CH + 129N + 20147 \quad (1)$$

$$HHV\ (PLS) = 5.22C^2 - 319C - 1647H + 38.6CH + 133N + 21028 \quad (2)$$

Where; C = carbon, H = hydrogen, N = nitrogen content expressed on a dry mass percentage basis. The reported calorific values were calculated using an average of the results from both two equations [10].

Example; Calculation of HHV of torrefied cassava rhizome at 260°C

Where; Carbon content = 42.8 wt%, d.b.

Hydrogen content = 4.9 wt%, d.b.

Nitrogen content = 2.3 wt%, d.b.

Ash content = 6.8 wt%, d.b.

Substitute equation (1) and (2);

$$HHV\ (OLS) = 1.87(42.8)^2 - 144(42.8) - 2802(4.9) + 63.8(42.8)(4.9) + 129(2.3) + 20147$$

$$= 17.4\ MJ/kg$$

$$HHV\ (PLS) = 5.22(42.8)^2 - 319(42.8) - 1647(4.9) + 38.6(42.8)(4.9) + 133(2.3) + 21028$$

$$= 17.3\ MJ/kg$$

$$HHV\ (d.b.) = (17.4+17.3)/2 = 17.35 \approx 17.3\ MJ/kg$$

$$HHV\ (d.a.f.) = 17.3/(1-0.068) = 18.6\ MJ/kg$$

2. Lower heating values of torrefied products

2.1 Torrefied solid

The lower heating value of biomass was calculated from its higher heating value and the heat of vaporization of water formed during its combustion reaction.

LHV = HHV – (heat of vaporization of water in the combustion product) (3)

Example; Calculation of LHV of torrefied cassava rhizome at 260°C

Where; HHV (d.b.) ≈ 17.3 MJ/kg

Hydrogen content = 4.9 wt%, d.b.

Molecular weight of hydrogen = 1 g/mole

Molecular weight of water = 18 g/mole

Latent heat of vaporization of water = 2,370 kJ/kg

Substitute equation (3)

LHV of 0.84 kg torrefied cassava (d.b.) = (17,300 – (0.049×9×2370)) ×0.84

= 13,654.1 kJ

2.2 Volatile products

There are 4 main volatile products released during pyrolysis process at 260°C of cassava rhizome. H_2O, CO and CO_2 are the non-condensable products and only CO that has the heating value. The condensable or tar was assumed as acetic acid which has a specific heating value.

The LHV used for the energy balances of this study are as follow;

LHV of CO = 10,000 kJ/kg

LHV of acetic acid = 14,370 kJ/kg

Therefore;

LHV of 0.003 kg CO = 10,000 × 0.003

= 30.0 kJ

LHV of 0.101 kg acetic acid = 14,370 × 0.101

= 1,451.4 kJ

3. Sensible heats of torrefied products

The sensible heat of torrefied product at pyrolysis temperature was calculated from equation (4)

Sensible heat = mcp$\triangle$T (4)

Where; m = mass of torrefied product

Cp = heat capacity of torrefied product

$\triangle$T = the difference between the pyrolysis temperature and the room temperature

Example; Calculation of sensible heat of torrefied products from slow pyrolysis of cassava rhizome at 260°C

The heat capacities used for the sensible heat calculation are as follow;

Heat capacity of torrefied solid = 1.04 kJ/kg °C

Heat capacity of steam = 1.87 kJ/kg °C

Heat capacity of CO_2 = 0.92 kJ/kg °C

Heat capacity of CO = 1.48 kJ/kg °C

Heat capacity of acetic acid = 1.06 kJ/kg °C

$\triangle$T = 260 – 25 = 235°C

Substitute equation (4)

Sensible heat of 0.840 kg torrefied solid = 0.840×1.04×235

= 205.3 kJ

Sensible heat of 0.043 kg steam = 0.043×1.87×235

= 18.9 kJ

Sensible heat of 0.043 kg CO_2 = 0.013×0.92×235

= 2.8 kJ

Sensible heat of 0.003 kg CO = 0.003×1.48×235

= 1.0 kJ

Sensible heat of 0.101 kg other or acetic acid = 0.101×1.06×235

= 25.2 kJ [21]