

# Energy and exergy in bark and other moist fuels

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(please notify errors)

## 1 Heating value and chemical exergy

We define *heating value* by thinking of a combustion chamber: Fuel and air are supplied at a certain temperature (that we have to choose based on some standard). It burns, and we take out so much heat that the combustion products are cooled down to the same temperature that the air and fuel had. Then, the released heat is the heating value.

*Lower heating value* (Norw.: "nedre brennverdi") is defined such that the reaction is complete and that all H<sub>2</sub>O of the combustion product is in vapor form. *Higher heating value* (Norw.: "øvre brennverdi") is defined correspondingly, except that all H<sub>2</sub>O of the combustion product is in liquid form. The difference between these two is equal to the heat of condensation of the water.

Biofuels usually contain water. Evaporation of this water takes some of the energy. We define *effective heating value* (also: net calorific value; Norw.: "effektiv brennverdi") as the lower heating value of the moist fuel (dry matter and water together).

*Chemical exergy* is the work that can be obtained from the fuel when it is brought to equilibrium with the surroundings through a reversible process. Thus, this is the maximum work from the fuel. The value is often close to the heating value.

When energy in fuels is quantified, it is (with no or very few exceptions) the lower heating value. For moist fuels, it is the effective heating value (lower heating value of the moist fuel).

## 2 Effective heating value

The lower heating value of the dry matter is  $h_{fs}$  (kJ/kg), the moisture content is  $w = m_{\text{water}}/m_{fs} + m_{\text{water}}$  (kg water per kg moist fuel), and the heat of evaporation of water is  $h_{fg}$ . Then, the effective heating value is:

$$h_{\text{eff}} = h_{fs} \cdot (1 - w) - h_{fg} \cdot w = h_{fs} - (h_{fs} + h_{fg})w. \quad (1)$$

This is the lower heating value of the mixture of dry matter and water; we have assumed that the water in the flue gas is vapor.

The heat of evaporation,  $h_{fg}$ , for water can be found from steam tables, e.g. in Moran and Shapiro (1998:721). The value is 2442.3 kJ/kg at 25 °C, 2528.9 kJ/kg at 15 °C, and 2501.3 kJ/kg at 0 °C.

For exercises we can use  $h_{fs} = 19$  MJ/kg (that is, per kg dry matter). Fresh bark typically has approximately 60 % moisture ( $w = 0.6$ ). With these values, we obtain  $h_{\text{eff}} = 6.1$  MJ/kg.

## 3 Chemical exergy

Here, we can use an empirical expression given by (Kotas 1995:267f): For dry, solid fuels with a certain content of oxygen, the ratio of chemical exergy to lower heating value is

$$\varphi_{\text{dry}} = \left( \frac{\varepsilon^{\circ}}{h_{\text{br,n}}^{\circ}} \right) = \frac{1.0438 + 0.1882 \frac{h}{c} - 0.2509 (1 + 0.07256 \frac{h}{c}) + 0.0383 \frac{h}{c}}{1 - 0.3035 \frac{h}{c}} \quad (2)$$

Here,  $h/c$  is the ratio of hydrogen mass to carbon mass in the fuel, and  $n/c$  and  $o/c$  correspondingly for nitrogen and oxygen. This expression is valid for  $o/c$  from 0.667 to 2.67, and is expected to be accurate within  $\pm 1\%$ . Superscript  $\circ$  shows that the value was taken at the reference state (25 °C, 1 atm).

This value is for the dry matter. For moist fuel, the ratio of chemical exergy to effective heating value becomes

$$\varphi = \frac{(\varepsilon^{\circ})_{\text{moist}}}{h_{\text{eff}}} = \frac{(1-w)\varepsilon_{\circ,fs}}{(1-w)h_{fs} - wh_{fg}} = \left( 1 - \frac{w}{1-w} \frac{h_{fg}}{h_{fs}} \right)^{-1} \varphi_{\text{dry}}. \quad (3)$$

For bark we can use the composition (mass basis) 50.0 % C, 6.1 % H, 42.7 % O, and 1.2 % N (analysis data may vary). This gives  $h/c = 0.123$ ,  $n/c = 0.024$ ,  $h/c = 0.853$ , and  $\varphi_{\text{dry}} = 1.072$ .

With  $w = 0.60$ ,  $h_{fs} = 19$  MJ/kg, and  $h_{fg} = 2.5$  MJ/kg, we get  $\varphi = 1.34$ ,  $h_{\text{eff}} = 6.1$  MJ/kg, and  $\varepsilon_{\circ} = \varphi \cdot h_{\text{eff}} = 8.2$  MJ/kg.