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การเผาไหม้และ
การวิเคราะห์อเวเลบิลิตีของเชื้อเพลิงชีวมวล
COMBUSTION AND
AVAILABILITY ANALYSIS OF BIOMASS FUELS

บทคัดย่อ

การเผาไหม้ของเชื้อเพลิงชีวมวลแข็งที่ใช้ในอุตสาหกรรมเกษตรหลาย ประเทศ เช่น ชานอ้อย, กาบและกะลาผลปาล์ม มีความซับซ้อนกว่าเชื้อเพลิง ไฮโดรคาร์บอนเหลว เนื่องจากมีธาตุอยู่ในเชื้อเพลิงถึงห้าตัว ได้แก่ คาร์บอน, ไฮโดรเจน, ออกซิเจน, ไนโตรเจน และกำมะถันแล้ว ยังมีความชื้นสูงอีกด้วย

งานนี้ได้แสดงวิธีประเมินค่าความร้อนและอเวเลบิลิตีเคมีของเชื้อเพลิง ชีวมวลแข็ง, ค่าปริมาณอากาศตามทฤษฎีที่ต้องการสำหรับการเผาไหม้ โดย สมบูรณ์หาได้จากการคำนวณ และได้ถูกนำมาเปรียบเทียบกับค่าปริมาณอากาศ ที่ใช้ในการเผาไหม้จริง ซึ่งคำนวณได้จากผลการวิเคราะห์ไอเสีย ได้แสดงวิธี ประเมินค่าเอนธาลปีและอเวเลบิลิตีของไอเสียและของไอน้ำในไอเสียไว้ด้วย.

ABSTRACT

Combustion of a biomass fuel containing C,H,N,O,S and moisture is studied. Its heating values and chemical availability are estimated. The theoretical air for complete combustion is determined and compared with the actual air/fuel ratio derived from a flue gas analysis. Enthalpies and availabilities in the dry flue gas and water vapour in the flue gas are also estimated.

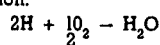## HEATING VALUES AND CHEMICAL AVAILABILITY

The higher heating value of a fuel, HHV, is normally obtained from a calorimeter where water vapour in the combustion product condenses and adds its latent heat to the heating value from the combustion. However, in practice, the flue gas temperature is usually much higher than the boiling point of water. The lower heating value of the fuel, LHV is often used as an alternative to take into account the loss of latent heat with the water vapour in the combustion product.

$$LHV = HHV - m_v \cdot h_{fg} \quad \text{......................(1)}$$

where h_{fg} = latent heat of vaporization of water,

m_v = mass of water vapour from the combustion of 1 kg of fuel.

If H is the percentage of free hydrogen in the fuel, by mass, the value of m_v is then 9H which is a result of the following combustion equation:

$$2H + \tfrac{1}{2}O_2 \rightarrow H_2O$$

2 kg 16 kg 18 kg.

A heating value is approximately the amount of chemical energy in the fuel. The chemical availability of a fuel, a_{ch}, indicates the potential work or available work in the fuel and can be determined from the following empirical equation[1]; in MJ/kg:

$$a_{ch} = LHV \left[1.044 + 0.0013 \frac{X_H}{X_C} + 0.108 \frac{X_O}{X_C} + 0.055 \frac{X_N}{X_C} \right] + 6.74 X_S \quad \text{.(2)}$$

where: X_H, X_C, X_O, X_N and X_S are the mass fractions of H,C,O,N and S in the dry fuel.

EXAMPLE 1 : A biomass fuel for a palm oil mill has the following compositions by mass: 33% C, 4.1% H, 0.8% N, 23% O, 0.1 % S and 36% moisture. Determine its LHV and chemical availability if its HHV is 12,450 kJ/kg of dry fuel.

From steam Table, at 1 atmosphere, 27 C, h_{fg} = 2258 kJ/kg.

Mass of dry fuel per 1 kg of fuel as fired = 0.64 kg.

Mass of H_2O from combustion per 1 kg. of dry fuel

$$= \frac{9 \times 0.041}{(1-0.36)} = 0.577 \text{ kg.}$$

Hence, from Equation (1), LHV of the dry fuel

$$= 12,450 - 0.577 \times 2258 = \underline{11,150 \text{ kJ/kg}} \text{ of dry fuel.}$$

From Equation (2), the chemical availability of the dry fuel

$$= 11.13 \left[1.044 + 0.0013 \times \frac{4.1}{33} + 0.108 \times \frac{23}{33} + 0.055 \times \frac{0.8}{33} \right]$$
$$+ 6.74 \times \frac{0.001}{0.64}$$

$$= 12.47 + 0.010 = \underline{12.48 \text{ MJ/kg}}$$

If the compositions of the fuel are not available, the chemical availability may be taken as approximately equal to HHV.

THEORETICAL AIR FOR COMBUSTION

The amount of air which is theoretically required for a complete combustion can be estimated from combustion equations of combustible elements namely C,H,S, in the fuel. For the biomass fuel in Example 1, the theoretical air/fuel ratio can be determined as follows:
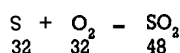
EXAMPLE 2 : Consider 1 kg of the fuel as fired.

$$\begin{array}{ccc} C & + O_2 & \rightarrow CO_2 \\ 12 & 32 & 44 \end{array}$$
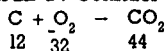
Mass of oxygen required for 0.33 kg of C $\frac{32}{12} \times 0.33 = 0.880$ kg.

$$\begin{array}{ccc} 2H & + \tfrac{1}{2}O_2 & \rightarrow H_2O \\ 2 & 16 & 18 \end{array}$$
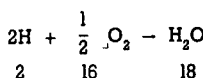
Mass of oxygen required for 0.041 kg of H = $\frac{16}{2} \times 0.041 = 0.328$ kg.

$$\begin{array}{ccc} S & + O_2 & \rightarrow SO_2 \\ 32 & 32 & 48 \end{array}$$

Mass of oxygen required for 0.001 kg of S = $\frac{32}{32} \times 0.001 = 0.001$ kg

Since the biomass contained 0.23 kg of oxygen, mass of oxygen required from air = 0.880 + 0.328 + 0.001 – 0.23
= 0.979 kg.

As air contains 23.2 % oxygen by mass, mass of theoretical air required for a complete combustion :

$$= \frac{0.979}{0.232} = 4.22 \text{ kg.}$$

Hence the theoretical air/fuel ratio = $\underline{4.22}$

FLUE GAS ANALYSIS

To ensure a complete combustion in practice, an excess amount of air above the theoretical air will be required. The actual air/fuel ratio may be estimated from the volumetric analysis of the dry flue gas by an Orsat Apparatus or other similar flue gas analyser.

EXAMPLE 3 : The dry flue gas from the combustion of the biomass fuel in Example 1 gives the following volumetric analysis : 79.7% N_2, 11.8% O_2 0.07% SO_2, 8.34% CO_2. The amount of unburnt carbon, by mass, is 2.4% of the fuel as fired.

Consider 1 mole of the dry flue gas.

By Avogadro's law, the volume of a gas varies as moles.

Mass of C to form 0.0834 moles of CO, $= 0.0834 \times 12 = 1.001$ kg.

% by mass of C burnt $= 33.01 - 24 = 30.6\%$.

Hence, mass of fuel as fired to form 1 mole of dry flue gas
$$= 1.001/0.306 = 3.27 \text{ kg.}$$

The mass of air required can be determined by the Oxygen Balance Method:

Mass of O in 0.0834 moles of $CO_2 = 0.0834 \times 32 = 2.67$ kg.
Mass of O in 7×10^{-4} moles of $SO_2 = 7 \times 10^{-4} \times 32 = 0.02$ kg
Mass of O, in the dry flue gas $= 0.118 \times 32 = 3.11$ kg
Mass of H in the fuel $= 3.27 \times 0.041 = 0.134$ kg
Mass of O to combine with the above H $= 0.134 \times 8 = 1.07$ kg
Mass of O in the fuel $= 3.27 \times 0.23 = 0.752$ kg
Mass of O, from the air $= 2.61 + 0.02 + 3.77 + 1.07 - 0.752$
$\qquad = 6.78$ kg
Mass of air required $= 6.18 / 0.232 = 29.2$ kg
Actual air/fuel ratio $= 29.2 / 3.27 = 8.93$

Check with Nitrogen Balance Method

Mass of N_2 in 1 mole of dry flue gas $= 0.797 \times 28 = 22.32$ kg
Mass of N in the fuel $= 0.008 \times 3.27 = 0.03$ kg
Mass of N_2 from the air $= 22.32 - 0.03 = 22.29$ kg
Mass of air used $= 22.29 / 0.268 = 29.02$ kg
Actual air/fuel ratio $= 29.02/3.27 = 8.88$

The nitrogen balance method seems to be simpler and more accurate since less measured data are used. The difference between the two methods is less than 1%.

ENTHALPY AND AVAILABILITY IN THE DRY EXAUST GAS

Excluding the mass of water vapour, the mass of the dry exhaust gas. m_e

$= $ mass of air + mass of fuel as fired
- mass of moisture - mass of free H in fuel
- mass of ash - mass of unburnt carbon

$$= m_a + m_f - m_m - m_H - m_{ash} - m_{c,un} \qquad (3)$$

If T_e, T_a = temperatures of the exhaust gas and ambient air, then:

Enthalpy increase in the dry flue gas. H

$$= m_e CP_e T_e - m_a CP_a T_a - (m_f - m_m - m_H - m_{ash} - m_{c,un}) C_s T_a$$

Simplification:

As $m_a \gg (m_f - m_m - m_H - m_{ash} - m_{c,un})$, C_s can be assumed as equal to CP_a.

Eence, H $\sim m_e CP_e T_e - CP_a T_a m_e$

$$\approx m_e \bar{C}_p (T_e - T_a) \qquad\qquad (4)$$

If should be noted that for complete combustion of light hydrocarbon fuels. m_m, m_{ash} and $m_{c,un}$ can be assumed as zero.

Hence. $m_e = m_a + m_f - m_H \qquad (5)$

EXAMPLE 4: After combustion, the biomass fuel in Example 3 yields, by mass, 3.15% ash and 2.35% unburnt carbon on the basis of the as fired fuel. Determine the losses in enthalpy and flow availability of the dry flue gas. The temperatures of the dry flue gas and ambient air are 325 and 30 C respectively.

From Equation (3) and Example 3,

$\qquad m_e = 8.88 + 1 - 0.36 - 0.0415 - 0.0315 - 0.0235$
$\qquad\qquad = 9.42$ kg per kg of as-fued fuel.

From Equation (4). H $= 9.42 \times 1.005(325 - 30)$
$\qquad\qquad = 2793$ kJ

AS a % of the HHV of fuel. the enthalpy loss with the dry flue gas

$\qquad = 100 \times 2793/12,480 = 22.4\%$

The above energy loss is rather large since the actual air used in combustion is much larger than the theoretical amount required. As Yo of the theoretical air. the actual air amounts to $8.88 \times 100/4.25 = 209\%$

By assuming that the dry flue gas is a perfect gas, the loss of flow availability with the dry flue gas can be estimated from the following equation (1):

$$A = m_e a_e - m_a a_a - (m_f - m_m - m_H - m_{ash} - m_{c,un})a_f$$

With the same simplification as before.

$$A \approx m_e \{h_e - h_a - T_o(s_e - s_a)\}$$
$$= m_e Cp(T_e - T_a - T_o \ln T_e / T_a)$$

Substitute the numerical values for the dry flue gas in Example 4,

$$A = 9.42 \times 1.005 [325 - 30 - (273 + 30) \ln \frac{273}{273} \times \frac{325}{30}]$$

$\qquad = 843$ kJ per kg of as fired fuel.

As a % of the fuel chemical availability,
$\qquad A = 843 \times 100/12,480 = 6.8\%$

The above loss of flow availability is the loss of potential work with the dry exhaust gas

ENTHALPY AND AVAILABILITY IN THE WATER VAPOUR

The water vapour in the exhaust gas comes from two sources namely the moisture in the fuel and combustion of hydrogen in the fuel. The datum for enthalpies is normally assumed at the ambient temperature, $T_a = T_o$

From Steam Table[3], state of water at 30 C,
$\qquad h_f = 126$ kJ/kg, $S_f = 0.436$ kJ/kg.K

Again, consider 1 kg of the fuel as fired. Mass of water vapour formed by combustion of hydrogen:

$\qquad = 9 X_H = 9 \times 0.0415 = 0.374$ kg.

Total mass of water vapour, $m_v = 0.374 + 0.36 = 0.734$ kg.

From Steam Table, at 325 C, 1 atmosphere.

h $= 3126$ kJ/Kg, s $= 8.291$ kJ/Kg.K

Enthalpy loss with the water vapour, $H_w m_v (h - h_f)$

$\qquad = 0.734(3126 - 126) = 2202$ kJ

As a % of the fuel chemical energy, H_w
$\qquad = 100 \times 2202/12,480 = 17.7\%$

Flow availability loss with the water vapour, A_w

$\qquad = m_v [h-h_f - To(s - s_f)]$

$\qquad = 0.734.[3126 - 126 - 300 (8.291 - 0.436) = 472$ kJ

As a % of the fuel chemical availability, A_w
$\qquad = 100 \times 472 / 12,480 = 3.8\%$

CONCLUSIONS

Combustion of a wet heterogeneous biomass fuel such as bagasse, oil palm wastes, etc. is more complex than liquid hydrocarbon fuels. The amount of actual air required for complete combustion is much larger than the amount of theoretical air. Hence, the energy and availability losses with the dry flue gas become quite large.

The moisture contents in the biomass fuels mentioned above are very high. Considerable amount of energy from combustion is required to vaporaize the moisture and added to the loss with the wet exhaust gas. The high temperature exhaust gas can be used for drying the wet fuel such as bagasse and thus the energy loss with the exhaust gas is reduced."

When a wet biomass fuel like the oil plam wastes is used as the boiler fuel, the first law and second law efficiencies of the boiler can be as low as 56% and 21% respectively[5] as a result of a large air/fuel ratio required for combustion and high moisture content in the fuel.

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