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COMBUSTION EFFICIENCY CHARTS FOR BIOFUELS USED IN CONDENSING APPLICATIONS

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ABSTRACT

The author recently published the first combustion efficiency charts for the combustion of biofuels, namely biodiesel and yellow grease. The charts give values of efficiency down to a stack temperature of 250 F. At this temperature no condensation of water vapour in the flue gas occurs. Condensing boilers, water heaters, and hot air furnaces are increasingly being utilized. In order to easily measure the performance of these devices or to do analysis of the effect of various changes (particularly important is the effect of stack oxygen content) one must utilize combustion efficiency charts for condensing equipment. This paper describes the development of charts for this application and gives charts for two important biofuels: biodiesel and yellow grease. Since these charts are the first publication of results of this type, the paper represents an important milestone in two areas that are evolving in mankind's quest to secure a renewable energy supply and to reduce harmful emissions by operating equipment on biofuels at maximum efficiency (i.e. utilizing latent heat in stack gases through condensation).

1. INTRODUCTION

Boilers, water heaters, and hot air furnaces are major consumers of energy in the world. As prices for fuel increases, interest in improving efficiency increases [1]. One significant way to improve efficiency is to condense flue gas and recover latent energy from the condensation process. Savings in the order of 5 to 15 per cent are possible depending on the type of fuel burned. Condensation of flue gas does pose some engineering challenge due to the corrosive nature of the liquids formed in condensation. However, use of modern materials has allowed equipment to be designed that overcomes the corrosion problem [2]. As a result condensing boilers, water heaters, and hot air furnaces numbering in the millions are in use in the world. Because of environmental issues, there also is a strong interest in turning to renewable fuels such as biodiesel.

In order to measure the performance of combustion equipment one generally uses an indirect technique generally called "combustion efficiency". In this method one measures the difference between the energy leaving the stack and the incoming energy in the fuel and air. This difference divided by the energy available in the fuel is the combustion efficiency. Charts for different fuels have been developed for conventional, non-condensing equipment [3]. A recent paper by the author included charts for biofuels [4]. This paper extends that work to include biofuel combustion with condensing flue gas. Tables are given for combustion of biodiesel and yellow grease.

2. FUEL CHARACTERISTICS

Table 1 lists the heating value and ultimate analysis for two biofuels taken from references [5], [6]. These references also give details about the type fuel considered. These table data are the starting point for developing combustion efficiency charts.

Table 1: Heating Value/ Ultimate Analysis of Two Biofuels

Fuel	Yellow Grease [5]	Biodiesel [6]
HHV, KJ/kg	39,341	39,664
Mole Fraction of Carbon, %	.50746	.49573
Mole Fraction of Hydrogen, %	.46229	.48563
Mole Fraction of Nitrogen, %	.00009	.00005
Mole Fraction of Oxygen, %	.03014	.01892
Mole Fraction of Sulfur, %	.00010	.00000

The ultimate analysis given in references [5] or [6] is in terms of mass fractions. In Table 1 the reference values are converted to mole fractions using the following relationship.

$$X_i = (M_{fi}/W_i) / (\sum(M_{fi}/W_i) \qquad (2.1)$$

Where W_i is the molecular weight of the substance i, the summation is over all species in the fuel, $M_{fi,}$ is the mass fraction of a species i, in the fuel and X_i is the mole fraction of species i in the fuel. A general chemical formula for a bio fuel is written as

$$\alpha\ C_AH_B+\alpha_1N_2+\alpha_2H_2O+\alpha_3O_2+\alpha_6S_2+\alpha_7CO_2 \qquad (2.2)$$

where:

$\alpha_1 \ldots\alpha_n$ are moles of respective species in the fuel, and
C_AH_B = an equivalent hydrocarbon fuel

Depending on the fuel analysis, some of the mole fractions, $\alpha_{i,}$ have definite values while all others will be zero. From this general fuel formula one can determine:

1. An equivalent hydrocarbon fuel (i.e. values of A and B),
2. The molecular weight of the fuel, and
3. The enthalpy of formation of the fuel.

Reference [4] shows how these calculations are made. The results are summarized below.

$$A = (W_{hydrocarbon} - B)/12 \qquad (2.3)$$

$$B = W_{hydrocarbon}(1 + M_{fCarbon}M_{fHydrogen}) \qquad (2.4)$$

Where $W_{hydrocarbon}$ is the molecular weight of the equivalent hydrocarbon in the fuel (assumed to be 1000 since fuel properties are insensitive to the actual value as long as the value is large (The real value is unknown but is very large).

$$\alpha = 1- \alpha_1 - \alpha_2 - \alpha_3 - \alpha_6 - \alpha_7 \qquad (2.5)$$

(Assuming 1 total mole of fuel reacting and α_i represents the mole fraction of each species from Table 1)

$$W_F = \sum(\alpha_iW_i) \qquad (2.6)$$

Where W_F is molecular weight of the fuel and the summation is over all species in the fuel. The enthalpy of formation of the fuel is calculated assuming no water vapour in products by making an energy balance on the combustion process.

$$h_{fF} = HHV-(1/W_F)[394{,}123(\alpha A+\alpha_7)+141{,}137(\alpha B+2\alpha_2) +297{,}388\alpha_6] \qquad (2.7)$$

where:
HHV = the higher heating value of the fuel in KJ/kg obtained from a laboratory analysis and h_{fF} is the enthalpy of formation of the fuel in KJ/kg

3. DEVELOPMENT OF THEORY UNDERLYING EFFICIENCY CHARTS

The problem considered in this section is the development of the underlying theory for a set of charts which gives the combustion efficiency, theoretical Air Fuel ratio, and excess air for the complete combustion of a general fuel as described by equation (2.2) where some of the flue gas is condensed. This is done in two steps. First, the combustion efficiency assuming no condensation will be developed. Then an additional improvement in efficiency is calculated based on recovery of the latent heat in the water vapour of that portion of water vapour in the flue gas that is condensed. The amount of oxygen in the flue gas and the flue gas temperature are known in this situation. In addition, only CO_2, H_20, N_2, and SO_2 are present in the products. The amount of these constituents must be determined depending on the fuel type and oxygen level in the flue gas. The first step for calculating combustion efficiency with no condensation is developed in reference [4] but is summarized here for convenience.

3.1 Summary Method of Calculating Combustion Efficiency with No Condensation

For complete combustion of one mole of fuel with dry air, one obtains

$$\alpha C_AH_B+\alpha_1N_2+\alpha_2H_2O+\alpha_3O_2+\alpha_6S_2+\alpha_7CO_2+aO_2+3.76aN_2$$

$$\longrightarrow dCO_2+gO_2+hN_2+jH_2O+kSO_2 \qquad (3.1)$$

The per cent oxygen in the dry flue gas, PO2, will be known from measurement. Using that value and a mass balance on each element in the combustion equation (3.1) allows values for all the moles of species in the products of combustion listed in equation (3.1) (namely, d, g, h, j, k) to be determined as well as the values of the moles of oxygen per mole of fuel, a. Using these values, one can calculate the enthalpy of reactants and products in equation (3.1). These calculations are shown in detail in reference [4]. The equations for enthalpy are

$$h_1 = h_{fF} \qquad (3.2)$$

$$h_2 = 0 \qquad (3.3)$$

$$h_3= [(d+g+h+k)/\alpha](W_D/W_F)[\sum h_{fi}+1.04*(T_{FG}-23)]$$

$$+(j/\alpha)(18/W_F)[-13{,}454+1.84(T_{FG}-23)] \qquad (3.4)$$

Where h_1 is the enthalpy of fuel, h_2 is the enthalpy of combustion air assumed to be 0 for this case, h_3 is the enthalpy of the combustion products and T_{FG} is the temperature of flue gas in C. Hence, the percentage combustion efficiency is given by

$$\eta_C = \{|h_3| - |h_1 - h_2|\}(100)/HHV \qquad (3.5)$$

The value of combustion efficiency obtained from equation (3.5) is the value for no condensation. An increase in combustion efficiency must now be calculated due to condensation.

3.2 Calculation of Increase in Combustion Efficiency Due to Condensation

In order to calculate the improvement in combustion efficiency due to condensation of water vapour in the flue gas, one must first determine the fraction of water vapour that is condensed. In this analysis, the water vapour that exists in the exiting flue gas will be saturated since condensation is occurring. According to Dalton's law of partial pressures, the mole fraction of water vapour equals the ratio of partial pressure to total pressure. Since the partial pressure is equal to the saturation pressure, Pg, the mole fraction of water vapour in the exiting flue gas is Pg,/atmospheric pressure. Antoine's equation for saturation pressure as a function of temperature [5] is as follows

$$Pg = .1333(10\hat{}(8.07131-1730.63/T)) \qquad (3.6)$$

Where T is temperature in C, and Pg is saturation pressure in kPa. This equation gives excellent agreement with data in the temperature range used here. The number of moles of water vapour in the exiting flue gas, j2, is

$$j2 = (Pg/P_{atm})*(d+g+h+j2+k) \qquad (3.7)$$

where P_{atm} = atmospheric pressure in kPa

Solving equation (3.7) for j2 gives

$$j2= [(Pg/P_{atm})/(1 - (Pg/ P_{atm}))]*(d+g+h+k) \qquad (3.8)$$

The condensation of water vapour per mole of fuel is the difference between the water produced by combustion and the water vapour exiting in the flue gas, i.e.

$$W_{cond} = j - j2 \qquad (3.9)$$

The energy saved per mole of fuel due to condensation is the product of the moles of water condensed, W_{cond}, and the latent heat of water, h_{fg}, at the condensing temperature. Thus, the percentage points improvement in combustion efficiency ($\Delta\eta$) due to condensation is

$$\Delta\eta = (W_{cond} (h_{fg}) / HHV) \times 100 \qquad (3.10)$$

Adding the combustion efficiency without condensation (Equation 3.5) to the improvement in combustion efficiency due to condensation (Equation 3.10) gives the combustion efficiency with condensation as follows

Combustion efficiency with condensation as a per cent =

$$[|h3| - |h1 + h2| + (Wcond (hfg)] (100)/HHV \qquad (3.11)$$

Equation (3.11) is used to make the calculations shown in section 4.

3.3 Calculation of Excess Air

The actual air-fuel ratio can be computed from the known moles of oxygen, a, since air contains 4.76 moles for every one mole of oxygen. Multiplying the ratio of moles of air per mole of fuel by the ratio of the molecular weight of air (28.93) to the molecular weight of the fuel gives

$$AF = 4.76 \cdot a \cdot 28.93/W_F \qquad (3.12)$$

where AF is the air fuel ratio in mass of air per mass of fuel.

The theoretical air fuel ratio is obtained assuming complete combustion with no excess air and balancing Equation (3.1) i.e,

$$AF_{theoretical}=$$

$$(4.76W_{Air}/W_F)[\alpha(A+B/4)-\alpha_3+2\alpha_6] \qquad (3.13)$$

The excess air is the difference between the actual and theoretical air-fuel ratio expressed as a percentage of the theoretical air-fuel ratio, namely

$$\%Excess\ Air = (AF-AF_{theoretical})(100)/AF_{theoretical} \qquad (3.14)$$

4. RESULTS

Combustion efficiency charts for the two biofuels whose values are listed in Table 1 are developed using the equations and procedure described above. The charts are produced assuming complete combustion of the fuel and that the fuel and air enter at 23 C. These conditions can be changed but for most cases the results are sufficient. Table 2 is a combustion efficiency chart for yellow grease and Table 3 is for biodiesel.

The charts show that one can easily obtain data from simple stack analysis for the efficiency of the device burning the fuel. The data show what happens when the combustion is tuned or heat recovery is applied. Further value for these charts is obtained when one wants to check flow instrumentation. For example, the fuel flow rate can be measured and the air flow determined from the efficiency charts knowing the Air/Fuel ratio. This allows an analysis of the combustion air fan performance. Many other useful results also can be obtained. Examples include determining the effect of return water temperature on hot water systems, effect of moisture content in fuels, effect of fuel pressure, inlet air temperature, etc.

A very interesting finding from these charts is that the amount of condensation that occurs is highly dependent on the excess air used for combustion. This is a result of the fact that the dew point temperature of water vapour in the flue gas decreases rapidly with increasing excess air. The dew point temperature for the two fuels considered is shown in Table 4. Hence, the efficient operation of any condensing boiler requires that the boiler be tuned for the minimum practical level of excess air.

See Tables 2 through 4 after "References"

References

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[5]Adams, T.T., A demonstration of fat and grease as an industrial boiler fuel, *University of Georgia Outreach Service Research Report*, June 30, 2002.

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[7] Antoine, C., Tensions des vapeurs; nouvelle relation entre les tensions et les températures, *Comptes Rendus des Séances de l'Académie des Sciences,*Volume 10, 1888, pp681–684, 778–780, 836–837.

Table 2: Combustion Efficiency Chart for Biodiesel

Temp of flue gas less temp of comb air, C					0	5.6	11.1	16.7	22.2	27.8
% O_2	% Excess Air	Air Fuel ratio theoretical	Air fuel ratio	%CO_2	% Combustion Efficiency for Combustion of Biodiesel with Condensing Flue Gas					
0	0.0	14.5	14.5	15.5	97.7	97.1	96.4	95.4	94.3	93.2
1	4.6	14.5	15.2	14.7	97.7	97.0	96.3	95.3	94.1	93.2
2	9.8	14.5	15.9	14.0	97.6	97.0	96.1	95.1	93.9	93.1
3	15.5	14.5	16.7	13.2	97.6	96.9	96.0	94.9	93.6	93.0
4	21.9	14.5	17.7	12.5	97.5	96.8	95.9	94.7	93.3	93.0
5	29.1	14.5	18.7	11.8	97.5	96.7	95.7	94.5	93.2	92.9
6	37.3	14.5	19.9	11.0	97.4	96.5	95.5	94.2	93.1	92.8
7	46.6	14.5	21.2	10.3	97.3	96.4	95.3	93.9	93.0	92.7
8	57.4	14.5	22.8	9.6	97.2	96.2	95.0	93.6	93.0	92.6
9	70.0	14.5	24.6	8.8	97.1	96.0	94.7	93.2	92.8	92.5
10	84.8	14.5	26.8	8.1	96.9	95.8	94.4	93.1	92.7	92.3

Note: No condensation occurs for the data highlighted

Table 3: Combustion Efficiency Chart for Yellow Grease

Temp of flue gas less temp of comb air, C					0	5.6	11.1	16.7	22.2	27.8
% O_2	% Excess Air	Air Fuel ratio theoretical	Air fuel ratio	%CO_2	% Combustion Efficiency for Combustion of yellow grease with Condensing Flue Gas					
0	0.0	14.5	14.5	15.5	99.2	98.6	97.8	96.9	95.8	94.9
1	4.6	14.5	15.2	14.7	99.1	98.5	97.7	96.8	95.6	94.9
2	9.8	14.5	15.9	14.0	99.1	98.4	97.6	96.6	95.4	94.8
3	15.5	14.5	16.7	13.2	99.0	98.3	97.5	96.4	95.1	94.7
4	21.9	14.5	17.7	12.5	99.0	98.2	97.3	96.2	95.0	94.7
5	29.1	14.5	18.7	11.8	98.9	98.1	97.2	96.0	94.9	94.6
6	37.3	14.5	19.9	11.0	98.8	98.0	97.0	95.7	94.8	94.5
7	46.6	14.5	21.2	10.3	98.7	97.8	96.8	95.4	94.8	94.4
8	57.4	14.5	22.8	9.6	98.6	97.7	96.5	95.1	94.7	94.3
9	70.0	14.5	24.6	8.8	98.5	97.5	96.2	95.0	94.6	94.2
10	84.8	14.5	26.8	8.1	98.4	97.2	95.9	94.9	94.4	94.0

Note: No condensation occurs for the data highlighted

Table 4 Flue Gas Dew Point Temperature vs. Oxygen Percentage

% Oxygen in Stack Gas	Dew point for BioDiesel, C	Dew point for Yellow Grease, C
0	51.11	50.13
1	50.21	49.28
2	49.31	48.42
3	48.40	47.57
4	47.60	46.52
5	46.37	45.36
6	45.14	44.19
7	43.91	43.03
8	42.68	41.86
9	41.38	40.36
10	39.72	38.78