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Calculation of the air ratio in the case of firing gaseous fuels containing incombustibles

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Abstract
A short-cut equation for the calculation of the air ratio in the case of firing gases containing incombustibles has been derived on the basis of mass balances. The new equation requires the oxygen concentration and the amount of carbon dioxide in the combustion gas, theoretical oxygen and air requirements, and the content of incombustibles other than carbon dioxide in the fuel for the air ratio calculation. By using the equation, a theoretically correct calculation of the air ratio has been enabled.

INTRODUCTION

This paper reports a generalised short-cut equation, based on the fuel composition and the oxygen concentration in the combustion gas, which is of generally applicability.

The control of the air ratio in the combustion process is very important for reducing fuel consumption and pollutant formation.[1] Because the measurements of air/fuel flowrates in industrial combustion processes are not sufficiently precise, the air/fuel ratio control is generally performed in conjunction with flue gas analysis. The most common practice is to calculate the air ratio using the oxygen concentration in the flue gas. The currently available short-cut equations, e.g. $m=21/[21-(O_2)]$, are sufficiently accurate for fuels composed of combustibles only. However, calculation of the air ratio with conventional equations, derived by balancing nitrogen, oxygen and carbon dioxide, leads to considerable errors from true values especially for fuels containing incombustibles. Further, concentrations of N_2 and/or CO_2 in the combustion gas also have to be known to use the conventional equations[2]. The objective of this study is to derive a universally valid equation for the calculation of the air ratio and thus to contribute in enhancing the performance of combustion control in practical combustion processes.

FUELS CONSISTING OF COMBUSTIBLES ONLY

Consider two examples of firing hydrocarbons, methane and propane. For convenience, excess air combustion is considered and the formation of carbon monoxide is neglected, but CO formation can be considered properly in the case of incomplete combustion. The combustion reactions are as follows.

$$CH_4+m(2O_2+7.52N_2) \rightarrow CO_2+2H_2O+7.52mN_2+2(m-1)O_2 \quad (1)$$

$$C_3H_8+m(5O_2+18.8N_2) \rightarrow 3CO_2+4H_2O+18.8mN_2+5(m-1)O_2 \quad (2)$$

where, m represents the air ratio and each chemical formula represents the amount of each species for unit volume of fuel.

Because the flue gas analysis is performed for dry combustion gas, the oxygen concentration,[(O_2),vol.%], measured in the combustion gas and the resultant air ratio can be expressed as:

for methane

$$(O_2)=2(m-1)\times 100/[9.52m-1] \quad (3)$$

$$m=[200-(O_2)]/[200-9.52(O_2)] \quad (4)$$

for propane

$$(O_2)=5(m-1)\times 100/[23.8m-2] \quad (5)$$

$$m=[500-2(O_2)]/[500-23.8(O_2)] \quad (6)$$

There is a similarity in equations (4) and (6) that the stoichiometric oxygen (multiplied by 100) and air requirements appear as the coefficients in the denominator. The coefficient of oxygen in the numerator is the difference between oxygen requirement and the amount of carbon dioxide in the combustion gas.

Equations (4) and (6) can be rearranged to give simpler forms similar to the conventional equation, $m=21/[21-(O_2)]$:

$$m=[21-0.105(O_2)]/[21-(O_2)] \quad (7)$$

$$m=[21-0.0849(O_2)]/[21-(O_2)] \quad (8)$$

Equations (7) and (8) are theoretically correct expressions of the air ratio. Consideration of these equations shows that the conventional equation overestimates the air ratio. The discrepancies from true air ratios become larger at higher oxygen concentrations. The coefficients of (O_2) in the numerators of equations (7) and (8) are the differences between the theoretical oxygen requirement and the amount of carbon dioxide in the combustion products, divided by the theoretical air requirements. At this stage, the air ratio for fuels consisting of combustibles only can be generalised, on the basis of the regularity appearing in equations (7) and (8), as:

$$m=[100O_o-(O_o-CO_{2,p})(O_2)]/[100O_o-A_o(O_2)]$$
$$=[O_o-(O_o-CO_{2,p})(O_2)/100]/[O_o-A_o(O_2)/100] \quad (9)$$

or

$$m=[100O_o/A_o-(O_o-CO_{2,p})(O_2)/A_o]/[100O_o/A_o-(O_2)] \quad (10)$$

or

$$m=[21-(O_o-CO_{2,p})(O_2)/A_o]/[21-(O_2)] \quad (11)$$

where, $CO_{2,p}$ represents the amount of carbon dioxide in the exhaust gas generated by burning unit fuel(volume basis) and is calculated from fuel composition; (O_2) is the measured oxygen concentration in the exhaust gas(vol.%) and A_o and O_o are the theoretical air and oxygen requirements(Nm^3/Nm^3 fuel). Because equation (11) is a rigorous expression for calculation of the air ratio and has the simplest form, it is recommended for commercial clean fuels.

FUELS CONTAINING INCOMBUSTIBLES

There are many fuels containing incombustibles. In this study, by-product gases from steel works are taken as examples. The compositions of the gases are given in equations (12)-(14) for BFG, COG and LDG, i.e. blast furnace gas, coke oven gas and Linz-Donawitz converter gas, respectively. The gases contain CO_2 and N_2 in considerable amounts.

The combustion reactions for the gases considered are as follows[3]. Each reaction is based on unit volume fuel, e.g. $1Nm^3$ or 1 mol.

BFG

$$(0.207CO_2+0.22CO+0.032H_2+0.541N_2) + m(0.126O_2+0.474N_2)$$
$$\rightarrow 0.427CO_2+0.032H_2O+(0.541+0.474m)N_2+0.126(m-1)O_2 \quad (12)$$

COG

$$(0.031CO_2+0.003O_2+0.029C_2H_4+0.084CO+0.266CH_4+0.564H_2+0.023N_2)$$
$$+ m(0.94O_2+3.536N_2)$$
$$\rightarrow 0.439CO_2+1.154H_2O+(0.023+3.536m)N_2+0.94(m-1)O_2 \quad (13)$$

LDG

$$(0.178CO_2+0.001O_2+0.642CO+0.02H_2+0.159N_2)+m(0.33O_2+1.241N_2)$$
$$\rightarrow 0.82CO_2+0.02H_2O+(0.159+1.241m)N_2+0.33(m-1)O_2 \quad (14)$$

The oxygen concentration and the resultant air ratio can be expressed by the following equations :

BFG $$(O_2)=0.126(m-1)\times 100/[0.842+0.6m] \quad (15)$$
$$m=[21+1.4033(O_2)]/[21-(O_2)] \quad (16)$$

COG $(O_2)=0.94(m-1)\times100/[-0.478+4.476m]$ (17)

$m=[21-0.1068(O_2)]/[21-(O_2)]$ (18)

LDG $(O_2)=0.33(m-1)\times100/[0.649+1.571m]$ (19)

$m=[21+0.4131(O_2)]/[21-(O_2)]$ (20)

From these expressions, it can be seen that incombustibles in the fuel act as a positive contribution to the air ratio. Considering equations (16), (18) and (20) together leads to the generalised equation:

$$m=[21-(O_o-CO_{2,p}-N_{2,f})(O_2)/A_o]/[21-(O_2)] \quad (21)$$

Equation (21) is an extented expression to equation (11). The validity of equation (21) has been confirmed by many trials for various fuels. In using equation (21), only measurement of oxygen concentration in the combustion gas is required; the remaining items in the equation can be calculated from the fuel composition. If the fuel contains incombustibles or inerts other than CO_2 and N_2, e.g. He, Ar, SO_2, etc., only a modification of the coefficient in the numerator of equation (21) is necessary; that is, substitution of $N_{2,f}$ to $[N_{2,f}+He_{,f}+Ar_{,f}+SO_{2,f}+\ ...]$ where the subscript f denotes fuel. It is expected that equation (21) may resolve problems involved in the conventional equations and can enhance the combustion control in pratical combustion processes with better accuracy.

DISCUSSION

The derivation of equation (21) was motivated when the authors were investigating the combustion control method of steam generating boilers in which BFG were used as the main fuel[3,4]. In industrial combustion furnaces, it is generally acknowledged that the air ratio is low enough practically if the oxygen concentration in the flue gas is maintained around 2%. However, in this study, it was found that the air flowrate in the case of BFG firing far exceeded that expected by the conventional equation, $m=21/[21-(O_2)]$, in spite of the oxygen concentration indicating an amount lower than 2%. When calculating the air ratio when burning BFG, with the conventional equation, 3.5% (O_2) in the flue gas corresponds to an air ratio of 1.2. According to equation (21), 3.5% (O_2) corresponds to an air ratio of 1.48, far higher than 1.2 and a high excess air. To control the air ratio at 1.2, the oxygen concentration should be maintained as 1.6%. In *Table 1*, air ratios calculated by $m=21/[21-(O_2)]$ and equation (21) are summarized for comparison. The conventional equation always overestimates the air ratio for COG and underestimates for BFG and LDG. The absolute differences in the calculated values become larger as the portion of incombustibles in the fuel increases. These results may be a good proof for the inapplicability of the conventional equation in the case of fuels containing incombustibles. Other well-known conventional equations for the calculation of the air ratio, $m=1/[1-3.76(O_2)/\{(N_2)_p-N_{2,f}/G'\}]$ from nitrogen balancing and $m=1+(O_2)G'/0.21A_o$ from oxygen balancing, also cannot represent true air ratio and/or requires further N_2 concentration in the flue gas[2], a drawback in practical application. G′ represents the amount of dry combustion gas and $(N_2)_p$ is the nitrogen concentration in the combustion gas. Therefore, it can be said that there is no universally applicable equation for the calculation of the air ratio at present.

CONCLUDING REMARKS

It is suggested that equation (21) be used in calculating the air ratio because the equation is derived from exact combustion calculation and theoretically correct. Equation (21) can be used for all gaseous fuels including those containing incombustibles, although some modifications are necessary for solid/liquid fuels, fuels containing species other than considered in this study, such as sulfur and nitrogen compounds, and incomplete combustion[5].

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Table 1 Comparison of calculated air ratios

O_2 concentration (vol.%)	Calculated air ratio			
	$m=21/[21-(O_2)]$	Equation (21)[a]		
		BFG	COG	LDG
1	1.050	1.120	1.045	1.071
2	1.105	1.253	1.094	1.149
4	1.235	1.565	1.210	1.332
8	1.615	2.479	1.550	1.870
10	1.909	3.185	1.812	2.285
12	2.333	4.204	2.191	2.884

[a] Equation (21) corresponds to equations (16), (18) and (20) for BFG, COG and LDG, respectively.