Calculation of Derating Factor of Diesel Engine, Fuled By Gaseous By-Products of Steel Industry

Satwik Mishra, Arvind Kumar Jain, Tanmay Singh, Swapnil Anand

***Abstract* - High levels of power requirement and exhausting fossil fuels represent major challenge before the world at present. Situation now demands to move towards alternative fuels for meeting up with rising energy demands. Increasing availability of alternative gaseous fuels attract us to think in different direction rather than moving ahead with conventional exhaustible fuels. Some special gases produced as a 'free' by-product during industrial process in steel industry, serve as an attractive energy source for efficient power production. In this paper, output power of a diesel engine undergoing combustion of special gases (produced as a by-product during industrial processes in steel industry) has been estimated. Analysis is carried out using empirical relationship available from the literature. Factors under considerations are calorific value, molar changes, adiabatic flame temperature, compression ratio etc.**

Keywords: Steel Industry, Derating Factor, Gaseous byproducts

I. INTRODUCTION

In Steel industries generally emit three types of special gases i.e. coke-oven gas, blast furnace gas and converter gas. These gases exhibits exceptional combustion characteristics and can be used economically for generating energy through combustion reactions.

Coke-Oven Gas is produced during carbonization of coal to form coke. Coke-oven gas is a fuel gas having a medium calorific value that is produced during the manufacture of metallurgical coke by heating bituminous coal to temperatures of 900°C to 1000°C in a chamber from which air is excluded. Typically, coke-oven gas is obtained from a battery comprising a number of narrow, vertical chambers, or ovens (0.5m wide, 5m high and 12m long) built of silica brick that are separated by heating ducts, such that heat is transmitted to the coal through both sides of the chamber walls. The ovens are slightly tapered so that one end is wider than the other to facilitate the horizontal discharge of the coke. Crushed coal is charged from overhead bunkers into the ovens, which are sealed at each end by refractory-lined sheet doors and heated for about 24 hours. The hot coke is then discharged. About 12%, by weight, of the coal is converted into gas. The hot gases evolved from the coal pass through a gas space at the top of the oven and into a collecting main prior to quenching and treatment to remove dust, tar and oil, and gaseous impurities such as ammonia and hydrogen sulphide. The yield of gas is about 300 cu m per ton of dry charge.

Blast Furnace Gas is a by-product of blast furnaces where iron ore is reduced with coke into metallic (pig) iron. The gas has a very low heating value of around 0.9kWh/Nm3, which on its own is typically not high enough for combustion in a gas engine. It has a very low heating value because it consists of about 60 percent nitrogen, 18-20% carbon dioxide and some oxygen, which are not flammable. The rest is mostly carbon monoxide, which has a fairly low heating value already. It is commonly used as a fuel within the steel works, but it can be used in boilers and power plants equipped to burn it. It may be combined with natural gas or coke oven gas before combustion or a flame support with richer gas or oil is provided to sustain combustion. Particulate matter is removed so that it can be burned more cleanly. Blast furnace gas is sometimes flared without generating heat or electricity

Converter gas is created from pig iron during the steel production process. Steel-making technology can be categorized into two different processes: blow moulding or open hearth. Within the blow moulding process, the pig iron is refined with oxygen or air, lowering the carbon proportion and providing enough process heat to maintain the steel liquid. With 60% of the worldwide raw steel production, the Linz-Donawitz (LD) process, classified as a blow moulding process, is the most common production method to generate raw steel. On the other hand, the open hearth process extracts the oxygen of the added scrap and ore, requiring additional heat supply for the steel-making process. One of the most common open hearth processes is the electrical melting process. The gas consists of about 65% carbon monoxide, 15% carbon dioxide, 15% nitrogen and small amounts of hydrogen and methane.

II. PREVIOUS WORK

Francisco et al. predicted the performance of Internal Combustion engines fueled by producer gas and other low heating value gases in their research paper. To predict the engine performance working with such a fuel, a so called Engine Fuel Quality (EFQ) parameter has been developed by the authors. This parameter considers the combined effect of stoichiometric air–fuel ratio and stoichiometric mixture heating value, both depending on the producer gas composition.

S Dasappa has also estimated power from a diesel engine running on Natural Gas, Producer Gas and Bio Gas. He has also used influence of the fuel properties on the peak temperature and pressure for the analysis. From the results it was clear that the simple analysis using empirical relations seems to predict the power output of a diesel engine modified to operate on gas quite satisfactorily. The effects of these had been discussed and case studies were also presented. The effect of using a turbocharger was also presented.

III. PROPOSED METHODOLOGY

Empirical formulas were used to calculate different properties of Coke Oven Gas, Blast furnace Gas and Convertor gas.

1. Molecular Weight

A. Molecular Weight of Coke Oven Gas

0.055*28 + 0.02*44 + 0.32*16 + 0.519*2 + 0.008*32 + 0.07*14

= 9.814Kg/Kmol

$\rho = M*n/V = 9.814*40.89/1000 = 0.401 Kg/m^3$

B. Molecular Weight of Blast Furnace Gas

0.6*28 + 0.2*44 + 0.2*28

= 31.2Kg/Kmol

$\rho = M*n/V = 31.2*40.89/1000 = 1.275 Kg/m^3$

C. Molecular Weight of Converter Gas

0.6*28 + 0.15*44 + 0.002*32 + 0.248*28 Kg/Kmol

= 30.408 Kg/Kmol

$\rho = M*n/V = 30.408*40.894 gm/m^3 = 1.2435 Kg/m^3$

2. Calorific Values

A. Calorific Value of Coke Oven Gas

H_2*241.8 + CH_4*802 + CO*283 KJ/mol

= 0.519*241.8 + 0.32*802 + 0.055*283 KJ/mol

=397.69KJ/mol

= (397.69*1000/9.814) = 40523.66KJ/Kg

=16249.98KJ/m^3

B. Calorific Value of Blast Furnace Gas

CO*283 KJ/mol

= 0.2*283 KJ/mol

= 56.6KJ/mol

= (56.6*1000/31.2) = 1814.10KJ/Kg

= 2312.9KJ/m^3

C. Calorific Value of Converter Gas

CO*283KJ/mol = 0.6*283KJ/mol

= (169.8KJ/30.408gm)*(1000gm/Kg)

= 5584.05KJ/Kg of converter gas

= 6943.77KJ/m^3

3. Energy Density

A. Energy Density of Coke Oven Gas : Calorific Value * Density

= 16.24* 0.463

= 7.519 Kg/m^3

B. Energy Density of Blast Furnace Gas: Calorific Value * Density

= 2.31*1.267

= 1.069 Kg/m^3

C. Energy Density of Converter Gas:

Calorific Value * Density

= 5.58* 1.3004

= 7.256 Kg/m^3

4. Adiabatic Flame Temperature

A. Adiabatic flame temperature of Coke Oven Gas :

CO_2 = 2%

CO = 5.5%

CH_4 = 32%

H_2 =51.9%

O_2 = 0.8%

N_2 = 7.8 %

$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$ (1)

(32) (64) (64) (32)

$CO + ½ O_2 \rightarrow CO_2$ (2)

(5.95) (2.75) (5.5)

$H_2 + ½ O_2 \rightarrow H_2O$

(3)

(52) (26) (52)

Adding equation 1,2 and 3,we get

$32 CH_4 + 5.5CO + 52H_2 + 92.75O_2 + 7.8N_2 + (348.74-0.8x3.76= 345.74) N_2 \rightarrow 37.5CO_2 + 2CO_2 + 52H_2O + 64H_2O + 353.54 N_2$ (4)

(Obtained by entered oxygen)

$32 CH_4 + 5.5CO + 52H_2 + 92.75O_2 + 353.54N_2$---------$\rightarrow$ $39.5CO_2 + 116H_2O + 353.54 N_2$

(5)

TABLE 1. ENTHALPY OF FORMATION OF GASES

	O_2	CH_4	CO	N_2	CO_2	H_2O	H_2

h_f	0	74850	110530	0	393520	241820	0
h_t (298K)	0	0	0	8669	9364	9904	0

Where
h_f(kj/kg-mol)=heat of formation
h_t(kj/kg-mol)=enthalpy at adiabatic temperature
h_{298}=enthalpy at 298K

Enthalpy difference b/w adiabatic flame temp and room temp = heat of formation (product - reactant)

$39.5(h_t - h_{298})CO_2 + 353.54\,(h_t - h_{298})\,N_2 + 116(h_t - h_{298})H_2O = 37.5h_fCO_2 + 116h_fH_2O - 5.5COh_f - 32h_f\,CH_4$ ………(6)
After putting the values of h_f for all the compounds at equation (6), we get following equation:
$39.5h_tCO_2 + 353.54\,h_t\,N_2 + 116h_tH_2O =$ 44369857.26…………………………....(7)
Now applying hit and trial method
At 2000K we put the values of h_t for CO_2 , N_2 and H_2O= 36481954
At 2300K we put the values of h_t for CO_2 , N_2 and H_2O=42847436
At 2350 we put the values of h_t for CO_2 , N_2 and H_2O=43918666.84
At 2400 we put the values of h_t for CO_2 , N_2 and H_2O=449932224

So adiabatic flame temp for coke oven gas is = 2375 K

B. Adiabatic flame temperature of Blast Furnace Gas

CO_2 = 15%
CO = 60%
O_2 = 0.2%
N_2 = 24.8%
$CO + ½\,O_2 \rightarrow CO_2$ (8)
60 30 60

Complete equation
$60CO + 30O_2 + 15CO_2 + 112.8\,N_2 + 24.8\,N_2 \rightarrow$
(from O_2)
$60\,CO_2 + 137.6N_2 + 15CO_2$ (9)
$60CO + 30O_2 + 15CO_2 + 137.6N_2 \rightarrow 137.6\,N_2 + 75CO_2$ (10)

TABLE 2. ENTHALPY OF FORMATION OF GASES

	CO	O_2	N_2	CO_2
h_f	110530	0	0	393520
h_t at 298K	0	0	8669	9364

Where
hf(kj/kg-mol)=heat of formation
ht(kj/kg-mol)=enthalpy at adiabatic temperature
h298=enthalpy at 298K

Enthalpy difference b/w adiabatic flame temp and room temp = heat of formation (product - reactant)

75(ht -h298) CO_2 + 137.6 (ht- h298) N2
= 60hfCO_2 - 60COhf CO (11)
75ht CO_2 + 137.6ht N_2 = 18874554.4
By hit and trial method
At 2000K we get value =16478156
At 2200K we get value=18383129
At 2250K we get value=18861385
So adiabatic flame temp = 2250K

C. Adiabatic flame temperature of Convertor Gas :

N_2 = 60%
CO_2 = 20%
CO=20%

$CO + ½\,O_2$---------------→ CO_2 (12)
20 10 20

$20CO + 60N_2 + 37.6N_2 + 10O_2 + 20CO_2$
(from O_2)
→ $97.6N_2 + 40CO_2$ (13)

Complete equation:
$20CO + 97.6N_2 + 10O_2 + 20CO_2$ ----------→ $97.6N_2 + 40CO_2$ (14)

TABLE 3. ENTHALPY OF FORMATION OF GASES

	N_2	CO	O_2	CO_2
h_f	0	110530	0	393520
h_t at 298K	8669	0	0	9364

Where
h_f(kj/kg-mol)=heat of formation
h_t(kj/kg-mol)=enthalpy at adiabatic temperature
h_{298}=enthalpy at 298K

Enthalpy difference b/w adiabatic flame temp and room temp = Heat of formation(product - reactant)

$40(h_t - h_{298})CO_2 + 97.6(h_t - h_{298})N_2 = 20h_fCO_2 - 20h_f\,CO$ (15)
$40h_t\,CO_2 + 97.6h_tN_2 = 6880454.4$
AT 1000K the value is 4851350.4
At 1300K the value is 6301472
At 1400K the value is 6866688
So adiabatic flame temp is 1400K

IV. SIMULATION RESULTS

Table below gives the calculated values of different properties of Coke Oven Gas, Blast furnace Gas and Convertor Gas.

TABLE 4. CALCULATED PROPERTIES OF GAS

S. No	Properties	Unit	Coke Oven Gas	Blast Furnace Gas	Convertor Gas
1.	Molecular Weight	kg/ Mol	0.401	1.275	1.2435
2.	Calorific Value	MJ/ kg	16.24	2.31	5.58
3.	Energy Density	MJ/ m^3	7.519	1.069	7.256
4.	Adiabatic Flame Temperature	K	2375	2250	1400
5.	Theoretical Air Requirement	kg/ kg	13	0.6	1.363
6.	Molar Change Factor		0.58	0.66	0.71
7.	Compression Ratio		9.5	9.0	10.0
8.	Density	kg/ m^3	0.463	1.267	1.3004

As its well-known fact that power from a gas engine depends heavenly in change in compression ratio, adiabatic flame temperature, the energy density, change in the moles between product and reactant.

Considering all the factors mentioned above, we can summarize the empirical relationship as,

Derating Factor = $f\,(\mu_{f,}\ P_{f,}\ E_{f,}\ M_{f,}\ T_f)$}

Where μ_f and P_f factors due to change in compression ratio affecting efficiency and power output, M_f is the factor due to change in the mole factor between the reactant and products, E_f is the energy density factor resulting from the difference in the energy density of the fuels, and finally T_f is the temperature effect on pressure due to change in adiabatic (peak) temperature in the engine cylinder.

Further,

Power Output: {Rated Power * $f\,(\mu_{f,}\ P_{f,}\ E_{f,}\ M_{f,}\ T_f)$}

Based on above empirical formula, de-rating factors of the engine operating with different gaseous fuels coming out as the by-product in the steel industry have been calculated below:

I. De-rating Factor of Coke Oven Gas

RB33 model, three cylinder engine with a volumetric capacity of 3.3 lts, 1500 rpm has a nominal output of 28 kW. The engine has compression ratio of 15:1.Considering this engine to operate using coke oven gas as a fuel, de-rating factor can be calculated as follows:

a. Reduction of power output by 0.00206 % of natural gas because of energy effects (energy density of coke oven gas is approx. 0.00206 % of that of natural gas).
   Hence E_f = 0.00206
b. Reduction of CR from 15 to 9.5 will lead to reduction in power by 15.5 % (which indicates that P_f = 0.854) and reduction in efficiency by 8.25 % (which denotes the value of μ_f is 0.9175)
c. Reduction in the in the peak pressure by 0.5857 due to reduction in the moles. Thus,
   M_f = 0.5857
d. Increase in the peak temperature is here i.e. 2375K from that of diesel engine which is 2225, so it will lead to increase in power here by temperature factor, T_f =1.067
   Hence,

Derating Factor = $f\,(\mu_{f,}\ P_{f,}\ E_{f,}\ M_{f,}\ T_f)$
= 0.00206*0.845*0.9175*1.067*0.58 = 0.00988
Power Output: {Rated Power * $f\,(\mu_{f,}\ P_{f,}\ E_{f,}\ M_{f,}\ T_f)$}
= 28*0.00988= 0.27664 kW

II. De-rating Factor of Blast Furnace Gas

RB33 model, three cylinder engine with a volumetric capacity of 3.3 lts, 1500 rpm has a nominal output of 28 kW. The engine has compression ratio of 15:1.Considering this engine to operate using coke oven gas as a fuel, de-rating factor can be calculated as follows:

e. Reduction of power output by 0.0003 % of natural gas because of energy effects (energy density of coke oven gas is approx. 0.0003 % of that of natural gas).
   Hence E_f = 0.0003
f. Reduction of CR from 15 to 9.0 will lead to reduction in power by 18.0 % (which indicates that P_f = 0.82) and reduction in efficiency by 9.0 % (which denotes the value of μ_f is 0.91)
g. Reduction in the in the peak pressure by 0.66 due to reduction in the moles. Thus,
   M_f = 0.66
h. Increase in the peak temperature is here i.e. 2250 K from that of diesel engine which is 2225, so it will lead to increase in power here by temperature factor, T_f =1.067
   Hence,

Derating Factor = $f\,(\mu_{f,}\ P_{f,}\ E_{f,}\ M_{f,}\ T_f)$
= 0.0003*0.82*0.91*0.66*1.067 = 0.0001576
Power Output: {Rated Power * $f\,(\mu_{f,}\ P_{f,}\ E_{f,}\ M_{f,}\ T_f)$}
= 0.0001576*28= 0.0044 kW

III. De-rating Factor of Converter Gas

RB33 model, three cylinder engine with a volumetric capacity of 3.3 lts, 1500 rpm has a nominal output of 28 kW. The engine has compression ratio of 15:1.Considering this engine to operate using coke oven gas as a fuel, de-rating factor can be calculated as follows:

i. Reduction of power output by 0.00201 % of natural gas because of energy effects (energy density of coke oven gas is approx. 0.00206 % of that of natural gas).
Hence $E_f = 0.00201$

j. Reduction of CR from 15 to 10 will lead to reduction in power by 15.0 % (which indicates that $P_f = 0.85$) and reduction in efficiency by 7.5 % (which denotes the value of μ_f is 0.925)

k. Reduction in the in the peak pressure by 0.5857 due to reduction in the moles. Thus,
$M_f = 0.71$

l. Decrease in the peak temperature here i.e 1400 K from that of diesel engine which is 2225, so it will lead to decrease in power here by temperature factor, T_f =0.62
Hence,

Derating Factor = $f(\mu_f, P_f, E_f, M_f, T_f)$
= 0.00201*0.85*0.925*0.71*0.62 = 0.00069

Power Output: {Rated Power * $f(\mu_f, P_f, E_f, M_f, T_f)$}
= 0.00069* 28= 0.0194 kW

V. CONCLUSION

After finding different characteristics and determining derating factors for different by-products gases of steel industry, it may be concluded that these gases may be used as an efficient gaseous fuels. De-rating factors for given engine are 0.00988, 0.0044 and 0.0069 for coke oven gas, blast furnace gas and converter gas correspondingly. Coke oven gas and converter gas may be used as a fuel separately however blast furnace gas can be blended with any other gaseous fuels to be used as fuels since it has very low energy density and very low value of de-rating factor.

VI. FUTURE SCOPES

In this paper we have calculated derating factors for a diesel engine operating on gaseous byproducts of steel industry namely Coke Oven Gas, Blast furnace gas and Convertor gas. One needs to calculate the same for other fuels as well such as Syngas which is abundantly and easily available in rural areas. These results can also be validated by experimental research as well.

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