Emissions Analysis and A/F Determination

Assignment 02

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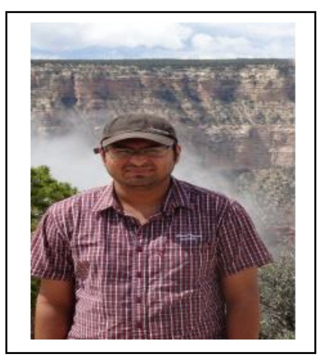

Introduction:

Combustion process is an exothermic reaction where fuel is made to react with an oxidizer and the heat generated is utilized to produce work. In the case of Internal Combustion (IC) engines, fuel is a hydrocarbon and oxidizer is air; the work produced is used to force the piston which in turn rotates the crank-shaft generating power. Also, the products of combustion, exhaust gases in this case, are carefully monitored to meet emission standards. Hence the combustion analysis is vital and affects the fundamental aspects of an engine viz., performance and emissions. This work helps to determine the air-fuel ratio from given fuel data (reactants) and emissions data (products). The assignment provides information on fuel data from which the HCR ratio is determined for analysis of the fuel and combustion reactions. Engine data provided is collected from two Cummins diesel engines – ISM 256 kW and ISL 272 kW. Data provided includes exhaust concentrations using several important parameters like combustion efficiency, fuel conversion efficiency, BSFC are determined. Data is collected from upstream DOC, downstream DOC and also through DCPF, but the analysis is performed only on the upstream DOC data. Several important conclusions can be made by analyzing the exhaust data, especially in terms emission requirement fulfillments and various efficiencies

I Development of solution and equation

The table described in the problem several columns which are computed as a part of the solution and each of the columns are explained in detail in this section

Engine speed is directly utilized from Table 3 provided with the assignment. Torque values are also provided in the table. These torque values are used to calculate power using the equation 1

$$P = \frac{2\pi NT}{60000} \qquad (1)$$

where

- N – speed in rpm

- T – torque in Nm
- P – Power in kW

Engine BMEP is calculated using the Equation 2

Equation 2

$$bmep = \frac{P * n_R * 10^3}{V_d N} \quad (2)$$

where

- bmep – brake mean effective pressure in kPa
- P – Power in kW
- nR – 2 for a 4S engine
- Vd – Volume displaced
- N – Revolutions per sec

In order to calculate volume displaced, the following table (Table 1) from the thesis has been utilized

Table 1 Important engine parameters

Table 3.1: Engine Specifications

Model	Cummins ISM-246 kW (330 hp)	Cummins ISL-272 kW (365 hp)
Year of Manufacture	2002	2007
Cylinders	6, inline	6, inline
Bore& Stroke	125 mm x 147 mm	114 x 144.5 mm
Displacement	10.8 L	8.9 L
Aspiration	Turbo Charged	Turbo Charged
Aftercooling	Cummins Charge Air Cooler	Cummins Charge Air Cooler
Turbocharger	Variable Geometry Turbine (Holset)	Variable Geometry Turbine (Holset)
Rated speed and Power	2100 rpm and 246 kW	2100 rpm and 272 kW
Peak Torque	1697 Nm @ 1200 rpm	1695 Nm @ 1400 rpm
Common Rail pressure (peak)	179 MPa	160 MPa
EGR system	Electronically controlled and cooled	Electronically controlled and cooled

Vd for ISM is 10.8L(or dm3) and Vd for ISL is 8.9L(or dm3)

Equation 1 and 2 have been calculated in MS-Excel as they do not involve complex calculations

A/F Ratio

Stoichiometric A/F ratio is a fuel specific parameter independent of the engine. Though the assignment does not provide a value for the molecular weight, it does provide weight ratios which can be used to calculate Stoichiometric A/F ratio by using the formula[1]

$$\left(\frac{A}{F}\right)_s = \frac{34.56 * \left(4 + y\right)}{12.011 + 1.008y} \qquad (3)$$

where

- y is Hydrogen to carbon ratio (HCR)
- A/F is Stoichiometric ratio

A/F ratio calculations presented in Appendix A and its value is determined to be **1.79**. At this stage the fuel can be assumed to be $C_nH_{1.79n}$. Data presented is in the form of C1 basis. Hence the entire analysis is done assuming the fuel as $CH_{1.79}$.

Before proceeding with determining actual A/F ratio, balance chemical equation is derived which is required for further analysis. Calculation procedure is provided in Appendix B. The balance equation is presented in Equation 4

$$CH_{1.79} + 1.45(O_2 + 3.773 N_2) \rightarrow CO_2 + 0.89 H_2O + 5.47 N_2 \qquad (4)$$

Actual A/F ratio and mass flow rates

To calculate the actual A/F ratios, Tables F-1 and F-2 can be utilized for concentrations of the exhaust gases. The aim of this exercise is to calculate value of phi which can be converted A/F actual using equation 5

$$\phi = \frac{\left(\frac{A}{F}\right)_s}{\left(\frac{A}{F}\right)_a} \qquad (5)$$

The following equations 6 to 9 are made under the assumption that the fuel is C_mH_n for m=1 and n=1.79

$$n = n_p * (x_{HC} + x_{CO} + x_{CO2}) \qquad (6)$$

$$x_{H2} = x_{H2O} * \frac{x_{CO}}{K * x_{CO2}} \qquad (7)$$

$$2 * \frac{n_{O2}}{\phi} = n_p * (x_{CO} + 2 * x_{CO2} + x_{NO} + 2 * x_{O2} + x_{H2O}) \qquad (8)$$

$$x_{H2O} = \left(\frac{m}{2 * n}\right) * \frac{x_{CO} + x_{CO2}}{1 + \left(\frac{x_{CO}}{k * x_{CO2}}\right) + \left(\frac{m}{2 * n}\right) * (x_{CO} + x_{CO2})} \qquad (9)$$

Where

- n_{O2} – the Stoichiometric moles of oxygen
- n_P – number of moles of product
- K – is a factor with a value of 3.8 [See Heywood 4.9.2]
- x_i – wet mole fraction concentration of ith component in exhaust [See tables F-1 and F-2]]
- x_i* - dry mole fraction concentration of ith component in exhaust

For this analysis it has been assumed that x_i and x_i* have similar values as value of x_{H2O} is quite small when compared to other concentrations and is not going to make significant difference in the calculations. These equations have been used directly from Heywood's section 4.9.2.

Equations also reveal that phi, n_P, x_{H2O} and x_{H2} are four unknowns and can be solved simultaneously by using equations 6 to 9. EES Code and the solution procedure are discussed in Appendix C.

The value of lambda, that is required, is calculated by reciprocating phi. Also Table 2 in appendix B has actual A/F ratio column which is also one of the desired results and can calculated from equation 5. Fuel flow rate is calculated by using equation 12

$$\dot{m}_{exhaust} = \dot{m}_{intake} \tag{10}$$

$$\dot{m}_{intake} = \dot{m}_{air} + \dot{m}_{fuel} = \dot{m}_{fuel}\left(1 + \frac{\dot{m}_{air}}{\dot{m}_{fuel}}\right) \tag{11}$$

From equations 10 and 11,

$$\dot{m}_{fuel} = \frac{\dot{m}_{exhaust}}{1 + \frac{\dot{m}_{air}}{\dot{m}_{fuel}}} \tag{12}$$

The value of $m_{exhaust}$ in kg/min from Table 3 of the assignment, especially for the passive oxidation case to develop the code presented in Appendix C. Also, it has to be realized that ratio presented in denominator in Eq 12 is the actual A/F ratio.

BSFC

Brake specific fuel consumption is one of the major parameters measured to test the efficiency of the engine. Every engine has a “sweet-spot” with lowest BSFC at which the engine can be optimized to run at for minimum fuel consumption, in other words maximum efficiency. BSFCs are measured as g/kW-h and usually lie in the range of 200 – 250 g/kW-h for diesel engines. BSFC can be calculated using the equation 13

$$bsfc = \frac{\dot{m}_f * 60 * 1000}{P} \tag{13}$$

where

- bsfc – brake specific fuel consumption in g/kW-h
- m_f – mass flow rate of fuel in g/min
- P – Power of the engine in kW

As this calculation is not as tedious as other calculations and the data from previous calculations is readily available, this calculation is made directly in EXCEL spreadsheet

Brake Specific Emissions (BSE NOx and BSE PM)

Table 3 of the assignment presents data on engine out PM concentration (mg/scm) which is basically mass per unit standard volume of exhaust. Table 4.19 presents exhaust volumetric flow rate data (volume per unit time) at average CPF temperatures. PM concentration is multiplied with exhaust flow rate to get a measurement of mass flow rate of PM (g/h). However, the volumetric flow rates in Table 4.19 of the assignment cannot be used directly as PM concentrations are evaluated as scm (standard cubic meter). These volumes should be converted to scm conditions before they can be used to calculate g/h of PM. Equation of state can be used to determine the volumes at standard conditions as average CPF temperatures are known. Here, an assumption is made that the pressure drop across CPF is negligible and as the exhaust is into the atmosphere at 100kPa, it has been assumed that pressure at the measurement location is also atmospheric. Under these assumptions, volume flow rates can be converted to scm using equation 14

$$\dot{V}_{scm} = \dot{V}_{exhaust}\left(\frac{T_{scm}}{T_{exhaust}}\right) \quad (14)$$

T_{scm} is assumed to be a constant value of 298K and the value $T_{exhaust}$ is obtained from the table. Also it has been assumed that Tscm = Texhaust. The calculations are made in excel spreadsheet and are presented in Appendix D. PM BSE is calculated using equation 15

$$BSE\ PM = \dot{V}_{scm} * \frac{Engine\ out\ PM\ conc}{P_{bhp}} * \left(\frac{60}{1000}\right) \quad (15)$$

Table 3 also has information on NOx/PM. As engine PM is known in from the previous step (Refer Appendix D), NOx (mg/scm) can also be calculated. BSE Nox can be calculated using the same previously used procedure. NOx BSE is given by Equation 16

$$BSE\ NOx = V_{scm} * \frac{Engine\ NOx\ conc}{Fbhp} * \left(\frac{60}{1000}\right) \tag{16}$$

NOx calculations are also presented in the same spreadsheet in appendix D.

Combustion efficiency

Combustion efficiency is calculated using the Equation 17

$$\eta_{combustion} = (H_P - H_R)/m_f Q_{HV} \tag{17}$$

In equation 17, calculation of denominator is not complex as the values of mass flow rate and Qhv are available from data and previous calculations. However, calculating enthalpies in the numerator needs to be calculated with available data.

Calculating H_R

Heat of the reaction is calculated using the Stoichiometric reaction equation Equation 4.

$$CH_{1.79} + 1.45(O_2 + 3.773 N_2) \rightarrow CO_2 + 0.89 H_2O + 5.47 N_2 \tag{18}$$

$$\text{13.79 kg of fuel + 6.92kmol 200.4kgof air -> 7.36 kmol = 213.8 kg products} \tag{19}$$

$$(\delta H) - (\delta U) - R(np - nr)T_A \tag{20}$$

Internal energy change in Eq 20 is Qhv = -42.8MJ/kg hence

$$\delta H = -42.8 + 8.314 * 10^{-3} * 0.44 * \frac{298}{13.79} = -\frac{42.64MJ}{kgoffuel}$$

$$\delta H = hp - hr$$

$$h_p = \frac{-393.52 + 0.89 * -241.83}{213.8} = 2.84\frac{MJ}{kg} offuel$$

$$h_R = 2.84 + 42.64 * \frac{13.79}{213.8} = \frac{5.59MJ}{kgoffuel}$$

H_R can be calculated by multiplying the mass flow rate of the fuel by this value of h_R.

For calculating H_p, mole fractions of exhaust constituents need to be converted to mass fractions (m_f). As the mass flow rate of the exhaust is known from the data, and standard heats of formation of the constituents are known, H_p can be calculated using,

$$H_p = m_e \left(\sum_i m_{f,i} H_i^{o} \right) \qquad (21)$$

where

- m_e is the mass of exhaust
- $m_{f,I}$ is the mass fraction of a constituent
- H^0_i is the standard heat of formation of a constituent

Calculations pertaining to conversion of mole fractions to mass fractions and actual calculations of combustion efficiencies are in Appendix E

Table consolidation

In lieu of the discussion and assumptions presented above, Table is filled with appropriate numbers

Table 2 Consolidated table for all the calculations made

Test	Eng Speed	Eng Power	Eng BMEP	A/F	λ	Fuel Flow	Comb. Eff. (η_c)	BSFC	Fuel Conv Eff.	NOx BSE	PM BSE
	(rpm)	(kW)	(BAR)	(-)	(-)	(kg/min)	(%)	(g/kW·h)	(%)	(g/bhp-h)	(g/bhp-h)
ISM-1	1170	62.5	2.97	26.25	1.81	0.2496	91	240	0.35	0.028	0.0021
ISM-2	1130	68.6	3.37	24.66	1.70	0.265	93	232	0.36	0.028	0.0019
ISM-3	1300	157.8	6.74	23.96	1.65	0.5769	94	219	0.38	0.047	0.0003
ISM-4	1270	199.4	8.72	20.91	1.44	0.7715	93	232	0.36	0.039	0.0004
ISM-5	1780	111.8	3.49	24.23	1.67	0.2655	93	143	0.59	0.020	0.0014
ISL-2	1290	74.3	3.88	24.92	1.72	0.2971	93	240	0.35	0.024	0.0004
ISL-1	1200	35.2	1.98	35.89	2.48	0.1518	92	259	0.32	0.052	0.0006
ISL-4	1520	165.5	7.34	21.78	1.50	0.6628	93	240	0.35	0.020	0.0004
ISL-5	1650	215.9	8.82	19.73	1.36	0.8682	93	241	0.35	0.016	0.0006
ISL-3	1290	75.6	3.95	24.08	1.66	0.307	93	244	0.35	0.025	0.0004

II Table discussion

From Table 2, it can be concluded that

- Power and BMEP of ISM is higher at comparable lower speeds, however, as the speed increases, ISL generated more power. As they are operating at part load, this comparison is not robust and engine characteristics mat change with varying loads.
- BSFC values are significantly higher when compared to Heywood as the book suggests that bsfcs below 200 g/kWh are attainable for large CI engines. However, at part loads the fuel efficiency does tend to be higher than lowest possible bsfc
- Fuel conversion efficiency of both the engines is almost similar at around 35%. ISL test-5 is an anomaly as it is not a passive oxidation test but a loading test

A. For ISM, volume per cylinder is 1.8, whereas for ISL volume per cylinder is 1.48. Comparable engine for ISM in Table 15.4 is DI/4S/TCAC(**=Engine A**) with max bmep 1560 kPa(=15.6 bar) occurring at 1500 rpm. Though this value seems to be higher than average bmeps presented in Table 2 for ISM, this value is incomparable because the engine was run at part load during the test. Rated torque occurs at only 1200rpm in the case of ISM unlike the engine form the table whose peak torque occurs at 1500rpm. Also rated speed of ISM is 2100 rpm against rated speed of the other engine at 2100 rpm. Comparable engine for ISL is DI/4S/TCAC with 115mm*140mm bore/stroke=(**Engine B**) and a bmep of 8.62 bar. ISL is definitely a better engine in terms of bmep as it capable of achieving these bmeps at part load. Also the rated speed of ISL is much lower at 2100rpm against 2700rpm for engine from table.

B.A detailed account of calculations and assumptions are presented in the previous section and appendix B and C. NOx and PM do not really have an impact on lambda or A/F ratio. NOx and PM are formed due to incomplete and inefficient combustion. Formation of NOx also does have a slight impact on efficiency as it is formed out of an endothermic reaction. But very low concentrations of NOx do not really show a significant variation in lambda in A/F values

C. Engine A has a bsfc of 195 g/kW-h which is achieved at its best efficiency of 43%. ISM however has achieved a bsfc of 135g/kW-h, at part load. Also it has an efficiency of 35% at these loads. Hence ISM is an efficient engine compared to engine A. Engine B has a best bsfc of 204g/kW-h with an efficiency of 42%. Efficiencies of ISL calculated are much lower(=35%) and bsfcs slightly higher(=240g/kWh) than this number. However, ISL is running at part load and will have better efficiencies when run at optimum engine loads.

D. Figure 3-9 in Heywood shows the combustion efficiencies over a range of equivalence ratios. IT can be seen that the combustion efficiency is higher for lean mixtures rather that rich mixtures because of unburnt fuel in case of latter. Equivalence ratios for ISL and ISM are in the range of 0.4-0.7 and in this range combustion efficiencies are above 90%. This is justified by calculated combustion efficiencies which are in the range of 92-93%. Hence the engines can be assumed to be combustion efficient.

E. BSE NOx of ISM is higher when compared to ISL. However both the engines tend to perform within the permissible NOx levels of 2 g/bhp-h for 2004 and 0.2 g/bhp-h for 2007. BSE PM of ISM is definitely higher that of ISL. However, the values are well below the permissible limits of 0.1 g/bhp-h of 1994 standard and 0.01g/bhp-h of 2007 standard. Hence, both ISM and ISL are operating well below the EPA standard thresholds.

Conclusions

Exhaust gas constituents can be analyzed rigorously to estimate number of performance parameters of an engine. It is not required for the analyzer to be aware of molecular weight of the fuel. As the report demonstrates, all the calculations can be made in terms of C1 basis and results can be obtained. It can also be deduced that diesel engines mostly run lean and have higher efficiencies because of this. Exhaust analysis is also important in order to determine the emission levels of an engine and check if the NOx and PM levels meet the EPA standards.

References

1. Heywood,J.B., *Internal Combustion Engines Fundamentals*, McGraw-Hill Inc, 1988.
2. Hutton, C.R. *An Experimental Investigation into the Passive Oxidation of Particulate Matter in a Catalyzed Particulate Filter*, Michigan Technological University, MS Thesis, 2010.

Appendix A

A/F ratio calculation

From Table 3.4 of [2],

Wt% of C = 86.94

Wt% of H = 13.06

As these constituents ass up to 100% and also it is specified that fuel is ULSD, the contents of sulfur, oxygen and other impurities have been neglected in calculating fule properties

$$HCR = \frac{\frac{wt\%\ of\ H}{Mol.wt\ of\ H}}{\frac{wt\%\ of\ C}{Mol.wt\ of\ C}}$$

$$HCR = \frac{\frac{86.94}{12.011}}{\frac{13.06}{1.008}}$$

$$HCR = 1.79$$

Appendix B

Calculation of co-effiecients for a balanced chemical equation

Consider the following equation

$$CH_{1.79} + R(O_2 + 3.773N_2) \rightarrow aCO_2 + bH_2O + 3.773RN_2$$

In this reaction it has been assumed that air contains 3.773 moles of Nitrogen for each mole of oxygen and the Nitrogen in air does not react or chemically inert and also a complete combustion event is assumed. (CO or soot is also not generated).

Oxygen balance

$$2R = 2a + b$$

Hydrogen balance

$$1.79 = 2b$$

$$b = 0.89$$

Carbon balance

$$a = 1$$

$$R = \frac{2 + 0.89}{2} = 1.45$$

Therefore balanced chemical equation is

$$CH_{1.79} + 1.45(O_2 + 3.773N_2) \rightarrow CO_2 + 0.89H_2O + 5.47N_2$$

Appendix C

EES code for determination of unknowns and solution procedure

Code

```
"Declaring constants"
n = 1
m = 1.79
k = 3.8
n_O2 = 1.4475
AF_s = 14.5
QHV = 42.8
h_R = 86.66
h_P = 44.03


"Equations 6 to 10"
n = n_p*(x_HC+x_CO+x_CO2)
x_H2 = x_H2O*x_CO/(k*x_CO2)
2*n_O2/phi = n_p*(x_CO + 2*x_CO2 + x_NO + 2*x_O2 + x_H2O)
x_H2O = (m/(2*n))*(x_CO+x_CO2)/(1+(x_CO/k*x_CO2)+(m/2*n)*(x_CO+x_CO2))


"Calculation of phi, lambda and A/F actual"
lambda = 1/phi
AF_actual = AF_s/phi

“Calculation of fuel flow rate”
mfDOT = meDOT/(1+AF_actual)
m_NOx = (x_NO)*n_p*30 + (x_NO2)*n_p*46
```

The code is used as backend logic for solving a parametric table with all the required parameters. Table 2 denotes transpose of parametric table generated in EES. This format is chosen in order to accommodate all the variables which EES processes. Also, in the table the shaded rows are the rows which are determined. First five columns correspond to ISM Engine and the next five to ISL.

Table 3 Parametric table generated by EES

	ISM					ISL				
x_O2	0.0963	0.0902	0.0875	0.0691	0.0886	0.0917	0.1268	0.0746	0.0603	0.088
x_CO2	0.0797	0.0862	0.0896	0.1022	0.0878	0.0854	0.0586	0.0977	0.1073	0.0889
x_CO	0.000128	0	0	0.000085	0.000151	0.000061	0.000072	0.000062	0.000082	0.000006
x_NO	0.000021	0.000082	0.000456	0.000388	0.000028	0.000191	0.000246	0.000184	0.000164	0.000213
x_NO2	0.000001	0.000138	0.000007	0.000011	0.000009	0.000016	0.000038	0.000021	0.000018	0.000015
x_HC	0.000097	0.000003	0.000061	0.000003	0.000091	0.000067	0.000088	0.000031	0.000014	0.000062
x_H2O	0.06668	0.07162	0.07424	0.08387	0.07297	0.07105	0.04989	0.08046	0.08768	0.07371
x_H2	2.82E-05	0	0	1.84E-05	3.3E-05	1.34E-05	1.61E-05	1.34E-05	1.76E-05	1.31E-06
n_p	12.51	11.6	11.15	9.776	11.36	11.69	17.02	10.23	9.311	11.24
meDOT	6.8	6.8	14.4	16.9	6.7	7.7	5.6	15.1	18	7.7
mf_fuel	0.2496	0.265	0.5769	0.7715	0.2655	0.2971	0.1518	0.6628	0.8682	0.307
phi	0.5524	0.5879	0.6052	0.6936	0.5984	0.5819	0.4041	0.6657	0.7348	0.6022
lambda	1.81	1.701	1.652	1.442	1.671	1.718	2.475	1.502	1.361	1.661
AF_actual	26.25	24.66	23.96	20.91	24.23	24.92	35.89	21.78	19.73	24.08

Appendix D

Calculation of BSE PM and NOx

Table 4 Calculation procedure for NOx and PM BSE

Exhaust flow rate(m3/min)	CPF Temperature K	V_scm (scm/min)	Power bhp	Engine PM conc(mg/scm)	BSE PM(g/bhp-h)	Nox/PM	Nox(mg/scm)	BSE Nox
0.188	600	0.093373	683.91	32.1	0.002147	12.9	414.09	0.0277
0.194	621	0.093095	777.78	30.6	0.001858	15.1	462.06	0.028056
0.441	684	0.192132	1555.56	5.4	0.000294	160.1	864.54	0.047087
0.551	736	0.223095	2011.5	7.1	0.000355	108.8	772.48	0.038672
0.192	631	0.090675	804.6	39.2	0.001423	13.9	544.88	0.019776
0.218	632	0.102791	737.55	6.9	0.000427	56.1	387.09	0.023973
0.136	525	0.077196	375.48	6	0.000589	88.7	532.2	0.052269
0.456	682	0.199249	1394.64	6.5	0.00035	57.8	375.7	0.020243
0.555	710	0.232944	1676.25	13.3	0.000642	24.6	327.18	0.015796
0.216	638	0.10089	750.96	7	0.000418	59.9	419.3	0.025033

Vscm is obtained from first two columns using equation 14. P_bhp is derived from previously known values of P in kW. Engine PM Concentrate is given in Table 3. BSE PM is calculated using

$$BSE\ PM = V_{scm} * \frac{EnginePMconc}{P_{bhp}} * (\frac{60}{1000})$$

Engine NOx conc = EnginePMConc*(NOx/PM). This value can be used to calculate BSE NOx

$$BSE\ NOx = V_{scm} * \frac{EngineNOxconc}{P_{bhp}} * \left(\frac{60}{1000}\right)$$

Appendix E

Calculation of combustion efficiency

Table 5 Table of mole fractions

O2	CO2	CO	NO	NO2	HC	H2O	H2	N2
0.0963	0.0797	0.000128	0.000021	0.000001	0.000097	0.06668	0.00002818	0.75704482
0.0902	0.0862	0	0.000082	0.000138	0.000003	0.07162	0	0.751757
0.0875	0.0896	0	0.000456	0.000007	0.000061	0.07424	0	0.748136
0.0691	0.1022	0.000085	0.000388	0.000011	0.000003	0.08387	0.00001836	0.74432464
0.0886	0.0878	0.000151	0.000028	0.000009	0.000091	0.07297	0.00003303	0.75031797
0.0917	0.0854	0.000061	0.000191	0.000016	0.000067	0.07105	0.00001336	0.75150164
0.1268	0.0586	0.000072	0.000246	0.000038	0.000088	0.04989	0.00001613	0.76424987
0.0746	0.0977	0.000062	0.000184	0.000021	0.000031	0.08046	0.00001344	0.74692856
0.0603	0.1073	0.000082	0.000164	0.000018	0.000014	0.08768	0.00001763	0.74442437
0.088	0.0889	0.000006	0.000213	0.000015	0.000062	0.07371	1.309E-06	0.74909269

Mole fractions of shaded constituents are determined using EES in Appendix C. Mole fraction of N2 is calculated by subtracting the sum of all constituents from 1.

Mass fractions are determined by assuming 1mole of mixture and calculating mass of each of the constituents using mole fraction and mol.wt. Mass fraction will then be

$$m_{f,i} = \frac{m_i}{\sum_i^n m_i}$$

Table 6 denotes the table of mass fractions

Table 6 Table of mass fractions

	mass fractions								
	O2	CO2	CO	NO	NO2	HC	H2O	H2	N2
ISM-1	0.106293	0.120959	0.000124	2.17E-05	1.5867E-06	4.61E-05	0.0414	1.944E-06	0.7311529
ISM-2	0.09944	0.130667	0	8.48E-05	0.0002187	1.43E-06	0.044413	0	0.72517405
ISM-3	0.096414	0.135751	0	0.000471	1.1088E-05	2.9E-05	0.046014	0	0.72130919
ISM-4	0.076056	0.154671	8.19E-05	0.0004	1.7404E-05	1.42E-06	0.051926	1.263E-06	0.71684505
ISM-5	0.097673	0.133087	0.000146	2.89E-05	1.4262E-05	4.32E-05	0.045249	2.2758E-06	0.72375697
ISL-2	0.101109	0.129474	5.89E-05	0.000197	2.536E-05	3.18E-05	0.044066	9.2068E-07	0.725036
ISL-1	0.140181	0.089078	6.96E-05	0.000255	6.039E-05	4.19E-05	0.031025	1.1145E-06	0.73928817
ISL-4	0.082156	0.147944	5.97E-05	0.00019	3.3245E-05	1.47E-05	0.049843	9.2508E-07	0.7197588
ISL-5	0.066352	0.162345	7.9E-05	0.000169	2.8472E-05	6.64E-06	0.05427	1.2125E-06	0.7167478
ISL-3	0.096979	0.134711	5.79E-06	0.00022	2.3763E-05	2.94E-05	0.045693	9.0161E-08	0.72233829

Table 7 Calculating efficiency

	m_exhaust	**H_products**	**H_Reactants**	**Hp - Hr**	**Combustion efficiency**
ISM-1	6.8	-11.14433977	-1.395264	-9.74907577	0.912588719
ISM-2	6.8	-12.00282055	-1.48135	-10.5214706	0.927655665
ISM-3	14.4	-26.36992306	-3.224871	-23.1450521	0.937376052
ISM-4	16.9	-35.15668529	-4.312685	-30.8440003	0.934094896
ISM-5	6.7	-12.05401734	-1.484145	-10.5698723	0.930168114
ISL-2	7.7	-13.47488115	-1.660789	-11.8140921	0.929081758
ISL-1	5.6	-6.7946614	-0.848562	-5.9460994	0.915201292
ISL-4	15.1	-30.09015833	-3.705052	-26.3851063	0.930106287
ISL-5	18	-39.26017179	-4.853238	-34.4069338	0.925939095
ISL-3	7.7	-14.00154865	-1.71613	-12.2854186	0.93499183

In table 7, Hp is calculated using the equation 21 as mass fractions and heats of formation of constituents are known from Table 3.3 Hey wood. Combustion efficiency is then calculated using equation 17

Grade Sheet

Student Name: Arjun Darbha .

Area	Points	Score
Cover Sheet	5	
Introduction	5	
Equations and documentation	40	
Table and Results	20	
Discussion of Results in Table	20	
Following format and instructions for report/codes/submission	10	
Total =	**100**	