

PERFORMANCE ANALYSIS OF COMBUSTION SYSTEMS

Navin Fogla, fogla.navin@gmail.com

Dr. E. Natrajan, enat123@hotmail.com

College of Engineering Guindy, Anna University, Chennai – 600025, Tamil Nadu, India

Abstract. The performance of a system using the products of combustion depends on the properties of the combustion products. For instance, the performance of a furnace, gas turbine and rocket nozzle depend on the gas temperature, gas composition, molecular mass of gas and specific heat ratio. In this paper, the equilibrium composition of combustion of some of the typical fuels are computed at various equivalence ratios and mixture inlet temperatures. The effects of such parameters on the performance of the system are analysed and suggestions are discussed for better performance and efficient utilization of energy.

Keywords: combustion performance, gas properties, equilibrium concentration

1. INTRODUCTION

In a system using the products of combustion, the performance mainly depends on the properties of the products of combustion. The main properties taken into consideration are inlet temperature, molecular mass, specific heats at constant volume (C_v) and constant pressure (C_p). From the above mentioned properties the characteristic gas constant (R) and ratio of specific heats (γ) can be calculated. Once the properties are known, the performance of the systems can be predicted easily using well established concepts.

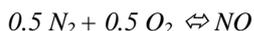
In the study conducted by Ceviz and Kaymaz (2005) temperature and air–fuel ratio dependent specific heat ratio functions were derived to minimize the error by using an equilibrium combustion model for burned and unburned mixtures separately. The results of the specific heat ratio function and experimental results were compared and were found to be in agreement with each other under lean operations of the engine.

Godin et al. (1998) accounted for the chemical reactivity of the hot combustion gases at high operating temperatures and presented a one dimensional model of the chemically reactive flow through the first turbine stage of an aircraft turbo jet engine. Three cases namely, sea level static operation, subsonic cruising and supersonic flights were analyzed. It was concluded that increase in performance is mainly obtained by increasing the inlet temperature.

2. METHODOLOGY

In the present work the hydrocarbon family of fuels is considered. The fuels considered are kerosene, gasoline, CNG (Compressed Natural Gas) and diesel. Gasoline is taken to be isooctane, diesel as cetane, CNG as methane and kerosene as $C_{10}H_{20}$. The values of C_v , C_p , R and γ of the mixture of the combustion products are calculated for various inlet temperatures ranging from 298 K to 3500 K and also for different air–fuel ratios.

The mole fractions of the products of combustion are calculated at different temperatures using the concept of equilibrium dissociation as described in Kuo (2005). The chemical reactions considered for the present work are the dissociation of carbon dioxide into carbon monoxide and oxygen, dissociation of water into hydrogen and oxygen and the production of nitrous oxide by the combination of nitrogen and oxygen. The dissociation reactions considered are shown below



The values of the equilibrium constants at different temperatures for the above reactions are taken from Kreith (2000) and the values of the equilibrium concentrations are calculated. The results of the calculation are compared with the results obtained in Kuo (2005) and are found to match exactly.

The values of C_p for the products of combustion at various temperatures are calculated using the relations provided in Smith (2000) and the values of R for the same are taken from Kreith (2000). The relation used for the variation of C_p with temperature is shown below

$$C_p/R = a + bT^2 + cT^3 + dT^4$$

where C_p – specific heat of compound at constant pressure

R – characteristic gas constant of each compound (kJ/kg.K)
T – temperature (K)
a,b,c,d – constants

After obtaining the values of C_p at various temperatures, properties like R, C_v and γ of the mixture of combustion products are calculated using the equation specified below

$$k = (\sum y_i k_i) / \sum y_i$$

where k – the required property (R, C_v or γ) of the mixture
 k_i – property (R, C_v or γ) of i^{th} constituent of the mixture
 y_i – mass fraction of i^{th} constituent of the mixture

The change in entropy due to mixing combustion products was also calculated by Nag (1982) by a simple procedure. The equation used for calculation of entropy change is shown below

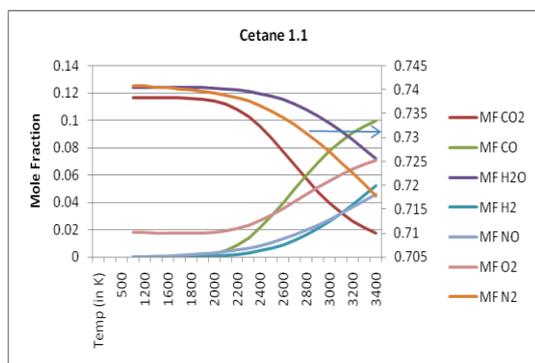
$$\Delta S = -R_u \sum n_i \ln x_i$$

where ΔS – change in entropy (kJ/kg.K)
 R_u – universal gas constant (kJ/kg.K)
 n_i – number of moles of the i^{th} constituent of the mixture (kg mol)
 x_i – mole fraction of the i^{th} constituent of the mixture

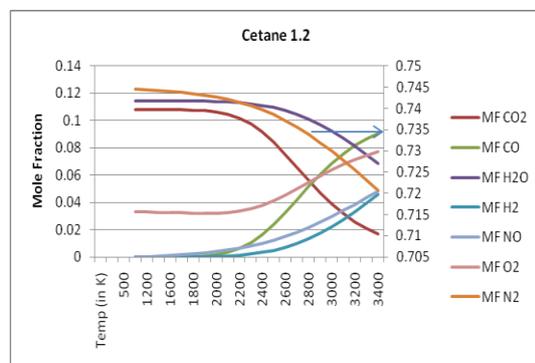
3. RESULTS OF CALCULATION

The results of the calculations can be separated into three categories - the variation of the product gas compositions, variation of the specific heat ratio with temperature and various equivalence ratios and the variation of entropy of the mixture of product gases

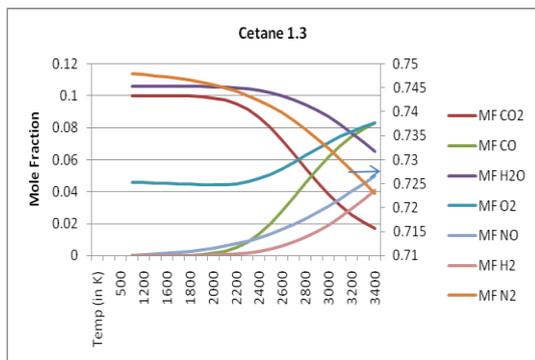
3.1. Product gas compositions at different temperatures and equivalence ratios



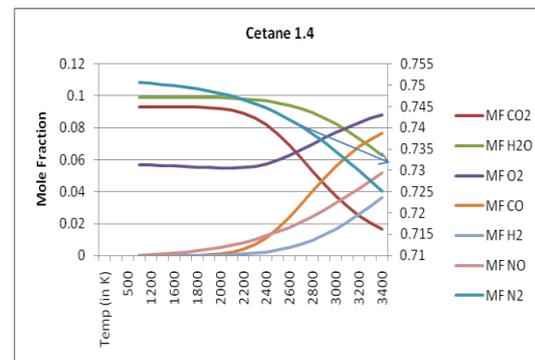
(a)



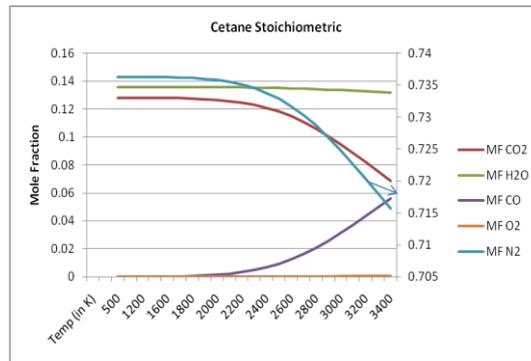
(b)



(c)



(d)



(e)

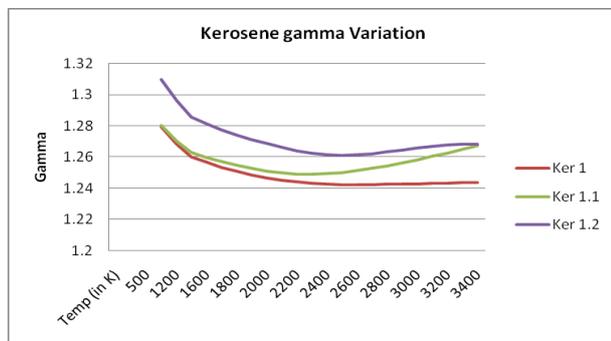
Figure 1. Product gas composition for cetane combustion with equivalence ratios (a) 1.1 (b) 1.2 (c) 1.3 (d) 1.4 (e) 1 (MF = Mole fraction)

Plots similar to the ones shown in Fig.1 are obtained for the other three fuels. It can be clearly seen from the plots that the concentration of the product gases stays fairly constant upto about 2000 K. After 2000 K distinct changes in the concentrations are noticed.

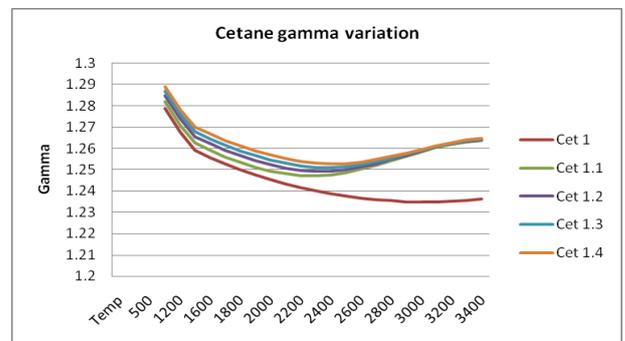
The concentration of CO₂ decreases while that of CO and O₂ increases, which can be attributed to the fact that dissociation of CO₂ into CO and O₂ begins at this temperature and the rate of the reaction increases with increase in temperature leading to a continuous decrease in CO₂ concentration and a continuous increase in CO and O₂ concentration beyond 2000 K. The decrease in the concentration of H₂O and the increase in the concentration of H₂ and O₂ occurs due to the same reason, namely increase in the rate of dissociation of H₂O.

At temperatures beyond 2000 K N₂ reacts with O₂ forming NO. This causes the decrease in the concentration of N₂ and the increase in the concentration of NO.

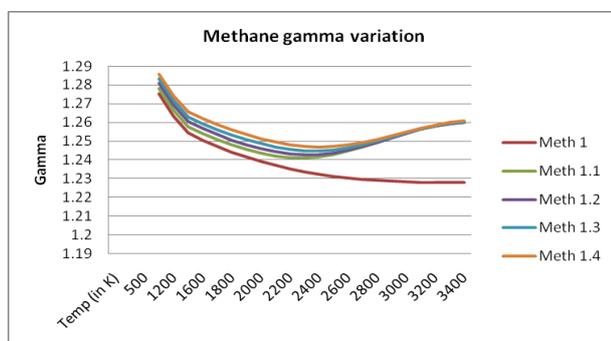
3.2. Variation of specific heat ratio with temperature and equivalence ratios



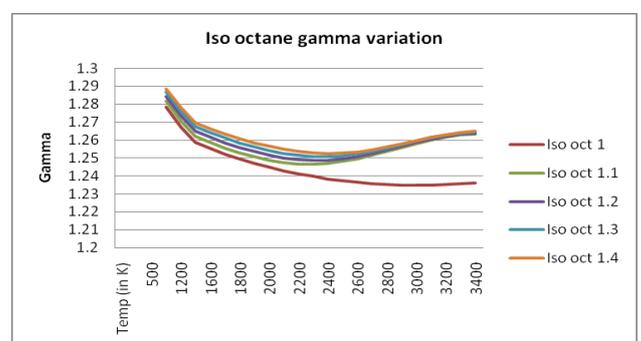
(a)



(c)



(b)



(d)

Figure 3. Variation of specific heat ratio with temperature and equivalence ratios for (a) Kerosene (b) Cetane (c) Methane (d) Isooctane (Ker = Kerosene, Cet = Cetane, Meth = Methane, Iso oct = Isooctane, the numbers represent the equivalence ratio)

The value of specific heat ratio decreases continuously with increase in temperature till about 2500 K for all the air fuel ratios. After 2500 K all the curves except for the stoichiometric curve, increase and converge close to a constant value whereas the stoichiometric curve continues to decrease even after 2500 K. The trend of γ is in agreement with the trend described in Ceviz and Kaymaz (2005) upto 2500 K. The distinctive behaviour of the combustion products above 2500K may be attributed to the dissociation reactions.

3.2. Variation of entropy of the mixture with temperature and air fuel ratio

The variation of entropy with temperature and air-fuel ratio is studied for the four fuels. A graph is plotted between entropy and temperature. The trend of the curve is increasing with temperature, gradual upto a temperature of 2200 K and a bit sharp after that.

As the air-fuel ratio is increased beyond stoichiometric, the curve shifts upwards. The shift of the curve varies from fuel to fuel, being the largest for kerosene and the least for methane.

The change in the entropy is an indication of the amount of heat energy that can be extracted from the fuel at the given inlet temperature. The higher the change in entropy the greater is the heat extracted from the fuel. As seen from the graph the greatest change in entropy occurs for cetane as compared to the other fuel.

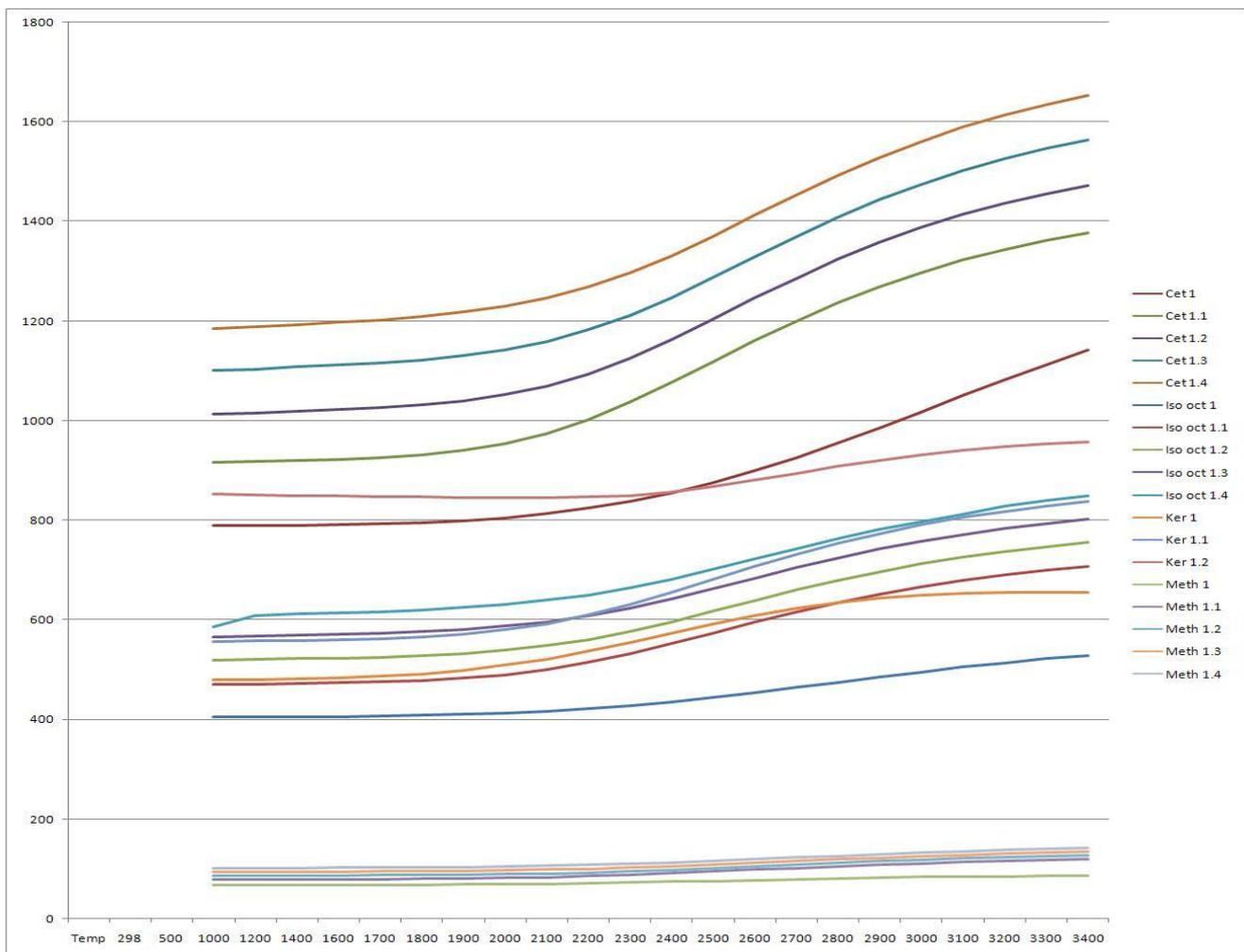


Figure 2. Entropy change of mixture for various inlet temperatures and equivalence ratios (Ker = Kerosene, Cet = Cetane, Meth = Methane, Iso oct = Isooctane, the numbers represent the equivalence ratio)

4. CONCLUSION

The composition and the temperature of the hot gases used in the thermal systems decide their performance. At temperatures below that of dissociation temperature the composition of N_2 is the maximum. When the temperature goes beyond that of dissociation the composition of CO_2 species is minimum and that of O_2 is maximum in all the cases

except the stoichiometric one. The composition of the product gas from the combustion process undergoes a considerable change in composition above certain temperature (2200K) due to product gas dissociation. The ratio of specific heats varies between 1.29 and 1.27 reaching a minimum of about 1.24. The effect of dissociation is also manifested in the value of the ratio of specific heats causing it to increase beyond the temperature of dissociation. The increased entropy of the mixture at very high temperatures indicates the increased loss of available energy, although theoretical efficiency increases due to increased combustion temperature. Optimum operating conditions may be arrived for individual cases based on the specific application

5. REFERENCES

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