JET ENGINE PERFORMANCE:

ADDITIONAL PARAMETERS

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ABSTRACT

Formulas for the ideal gas behavior of fluids were reviewed. A method of calculating adiabatic temperatures given the type of fuel and fuel air mixture is discussed. A program was created to calculate the adiabatic temperature using the discussed method. A program was made to calculate thrust from chamber temperature, ideal gas properties and inlet velocity. Results are discussed and graphed.

INTRODUCTION

Combustion of Hydrocarbon fuels provides the energy for the vast majority of jet engines. The complexities of a jet engine cause precise modeling to become complicated quickly due to three dimensional interactions between rotating and stationary parts and between other critical engine parts. Assuming one dimensional flow with ideal gas assumptions simplify the analysis. The jet engine will be analyized as a one dimensional system without a compressor or turbine. This approximates an ideal ram jet engine.

The objective is to determine the thrust of an idealized jet engine using the fuel air ratio and the type of fuel. Computer programs will be developed to calculate the adiabatic temperature and thrust when given the type of fuel and the fuel air ratio.

THEORY

A combustion where all Carbons and Hydrogens are oxidized with no remaining oxygen is a stoichiometric combustion. For Hydrocarbons of formula C_xH_y, the stoichiometric amount of oxygen m_s is $x + \frac{y}{4}$. The air equivalence ratio, AEQU, gives the ratio true moles of air to the stoichiometric moles of air. Thus, the Air Fuel Ratio (AFR) is

$$AFR = \frac{AEQU(x + \frac{y}{4})(32 + 3.76 \cdot 28)}{12x + y}$$

The general stoichiometric combustion chemical formula in air is

$$C_xH_y + (x + \frac{y}{4})(O_2 + 3.76) = xCO_2 + \frac{y}{2}H_2O + (x + \frac{y}{4})N_2 \tag{1}$$

Similarily, the formulas for fuel lean and rich can be found.

From the first law of thermodynamics, the heat added minus the work done equal the total energy change ($Q - W = E$). For an adiabatic process, the heat removed from the system, Q, is zero so that $E_{reactants} = E_{products}$. The total energy is calculated from the enthalpy of the system. The enthalpies of the components are calculated from a fitted curve where A,B and C are constants over a given temperature range.

$$h(T) = A + B \cdot T + C \cdot ln(T) \tag{2}$$

Similarly, the constant pressure specific heat is also calculated from the fitted curve as

$$C_p(T) = B + C/T \tag{3}$$

A overall product of combustion has properties of the mean of the individual products. Thus, the mean mixture molecular weight is

$$M = \Sigma(x_i M_i) = \Sigma(\frac{n_i}{n_t} M_i) \tag{4}$$

where n_i is the number of moles, n_t is the total product moles and M_i is the individual product's molecular weight. Similarly, the overall specific heat is

$$C_p(T) = \Sigma(C_{p_i} \frac{n_i}{n_t}) \tag{5}$$

From the molecular weight and specific heat, the specific gas constant and ratio of specific heats can be calculated.

$$R = \frac{\bar{R}}{M} \tag{6}$$

$$\gamma = \frac{C_p}{C_p - R} \tag{7}$$

The ratios of Static and Stagnation properties are derived from isentropic ideal gas equations as (John)

$$\frac{P}{P_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-\gamma}{\gamma-1}} \qquad \frac{T_t}{T} = \left(1 + \frac{\gamma - 1}{2} M^2\right) \tag{8}$$

In an isentropic nozzle, the ratios of temperature and pressure are related by (John)

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} \tag{9}$$

The Mach number in a nozzle can be found by taking (John)

$$\frac{p_t}{p} = \left(\frac{T_t}{T}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{p_t}{p} = \left(1 + \frac{\gamma - 1}{2} \cdot M^2\right)^{\frac{\gamma}{\gamma-1}}$$

Substituting, the exit Mach number of an isentroic nozzle as a function of the stagnation and exit temperatures is

$$M_{out} = \sqrt{\frac{2}{\gamma - 1} \cdot \left(\frac{T_t}{T_{exit}} - 1\right)} \tag{10}$$

Jet engines create thrust by continuously changing the momentum of a fluid. From the Material Derivative with steady state conditions,

$$\Sigma F = \frac{d(mv)}{dt} = \iint_{cs} V \rho \vec{V} \cdot \hat{n}\, dA$$

Control surface integration over input and output areas yields,

$$T = \Sigma F = (-u_{in}\rho_{in}u_{in}A_{in}) + (u_{out}\rho_{out}u_{out}A_{out}) \tag{11}$$

The incoming and exiting mass flow rates are

$$\dot{m}_{in} = \rho_{in}V_{in}A_{in}$$

$$\dot{m}_{out} = \dot{m}_{in} + \dot{m}_{fuel}$$

The Air Fuel Ratio (AFR) is the mass of air per mass of fuel. ($AFR = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}$) Thus, the exiting mass flow rate is

$$\dot{m}_{out} = \dot{m}_{in} \cdot \left(\frac{1}{AFR} + 1\right)$$

Substitutions into (11) yield

$$T = \dot{m}_{in} \cdot \left(\frac{V_{out}}{AFR} + V_{out} - V_{in} \right) \tag{12}$$

This gives the thrust of a jet engine with incoming and exiting streams at different velocities with fuel being added and with the inlet, exit and atmospheric pressures being equal.

METHOD OF CALCULATION

A computer program written in FORTRAN 77 (Appendix C) was developed to calculate the adiabatic flame temperature, molecular mass, ratio of specific heats and Gas constant of a specified hydrocarbon burning in air when given the air fuel ratio. The program first initilizes data for calculating product properties from previously fitted lines. An equation for the Air Fuel ratio is defined. Next, the variables are defined and an output file is opened. The type of fuel and its enthalpy of reaction are set.

A DO loop is used to step through air equivalence ratios. The products of combustion are calculated from the current equivalence ratio as shown above in the theory. Another DO loop creates a half interval search routine to find the adiabatic temperature. The search calculates the enthalpy of the products at a certain temperature, compares it with the adiabatic condition and adjusts the final temperature.

The program then calculates the product's molecular mass, Gas Constant, Constant Pressure Specific Heat and Ratio of Specific Heats. Calculated values for AFR, Temperature, Molecular Weight, Ratio of Specific Heat and Gas Constant are written to the screen and the a data file. The output file is closed and the program exits.

A computer program written in FORTRAN 77 (Appendix D)was developed to calculate the thrust of a jet engine when given air fuel ratios and the properties of the incoming fluid. The program first initializes real variables for the properties at each location. The input and output files are opened. Next, functions for $\frac{P}{P_t}$, $\frac{T}{T_t}$ and the Velocity of Sound given M, γ and T are defined. The conditions of the incoming stream are given and the incoming velocity is calculated.

A DO loop is used to step through every line in the data file and to input the Air Fuel Ratio, flame temperature, molecular weight, ratio of specific heats and gas constant of the burned mixture. Next, a nozzle is used to slow the flow to a Mach number of MENGINE ($PBURN = PATM * \frac{P/PT_{engine}}{P/PT_{inlet}}$). The total temperature is found from the inlet Mach number and the inlet temperature ($TTOT = T_{atm}T_t/T_{inlet}$). After combustion total temperature is calculated from the burn temperature and the previous total temperature ($TTOT_{burn} = T_{burn} + TTOT_{inlet}$). The chamber and exit pressure ratio is used to find the exit temperature from the stagnation temperature as shown in equation 9. From the temperature ratio, the Mach number at the exit of the isentropic nozzle is calculated as shown in equation 10.

Finally, the thrust calculations are made. The incoming mass flow rate is calculated. Thrust is calculated from equation 12. The AFR, Combustion temperature and thrust are written to the screen and a data file. Pressure, temperature, Mach number and Velocity of the inlet and exit locations are written to the screen. When the end of the input file is reached, the program closes the input and output files and exits.

RESULTS AND DISCUSSION

Calculations were performed as described above. The tabulated results for the adiabatic temperature computer program outputs are given in Appendix A Table 1 and plotted in Figures 1 through 4 in Appendix B. The results of the thrust computer program are given in Appendix A Table 2 and plotted in Figures 5 through 7 in Appendix B.

The adiabatic flame temperature of Kerosene and Air for Air Fuel Ratios (AFR) from 12 to 45 is given in Figure 1. The stoichiometric AFR is from theory near 15 and is easily seen in Figure 1 as the peak of the temperature curve. The temperature drops off rapidly after exceeding the stoichiometric Air Fuel Ratio. Likewise, the ratio of specific heat (Figure 2), specific gas constant (Figure 3) and mean molecular weight (Figure 4) all rapidly change in the vicinity of the stoichiometric ratio.

Thrust calculations from the adiabatic temperature and Air Fuel ratio are given in Figure 5. Clearly, the thrust magnitude follows the magnitude of the adiabatic temperature with a maximum thrust at the stoichiometric point with a similar rapid drop off in magnitude after the stoichiometric point. A plot of thrust versus the chamber temperature (Figure 6) shows how much the thrust follows the chamber temperature by the near linear relationship after the stoichiometric temperature. Related to this plot is th e metallurgical properties of the jet engine parts. Since current metals are limited in temperature to around 1500 K, better materials with more heat tolerant properties can easily increase the thrust over current jet engines. A plot of thrust versus inlet Mach number is given in Figure 7. The thrust increases steadily after Mach 0.8. Because the modeled engine is similar to a ram jet engine, it is seen that a ram jet engine cannot provide thrust when stationary and must be taken to almost a sonic region before providing much thrust.

CONCLUSIONS

This model used the combustion of Hydrocarbon fuels to provides the energy to create thrust. Assuming one dimensional flow, no compressor or turbine and ideal gas assumptions simplified the analysis. This simple model while not accounting for the moving and transient conditions of a real jet engine was able to find the underlying relations between thrust, the type of fuel and the Air Fuel Ratio.

REFERENCES

John, James E. A. (1984)

Gas Dynamics, Prentice Hall.

APPENDIX A:

Tabulated Results

APPENDIX B:

Figures

APPENDIX C:

Computer Program

APPENDIX D:

Computer Program

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8