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Automotive Gas Turbine Power System-Performance Analysis Code

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ABSTRACT

An open cycle gas turbine numerical modelling code suitable for thermodynamic performance analysis (i.e. thermal efficiency, specific fuel consumption, cycle state points, working fluid flowrates etc.) of automotive and aircraft powerplant applications has been generated at the NASA Lewis Research Center's Power Technology Division. The use of this code can be made available to automotive gas turbine preliminary design efforts, either in its present version, or, assuming that resources can be obtained to incorporate empirical models for component weight and packaging volume, in a later version that includes the weight- volume estimator feature. The paper contains a brief discussion of the capabilities of the presently operational version of the code, including a listing of input and output parameters and actual sample output listings.

INTRODUCTION-BACKGROUND

This numerical analysis tool is based on the BRMAPS closed Brayton Cycle code developed for space and planetary power systems (refs. 1 to 5), using either nuclear or concentrated solar heat sources. The power levels for these systems ranged from 10's of kilowatts to multimegawatts, and the cycle working fluid was an inert gas, such as helium-xenon mixtures in varying mol-fractions, depending on power level.

Written in a scientific programming language, known as VSAPL, the code utilizes several interconnected sub-programs to execute the thermodynamic performance calculations and carry out the mass computations for the essential sub-systems and components, based on empirical mass models for each component. The code also computes the mass for the overall system, comprising these components plus interconnecting structure and ducting. A key feature of the code is that for a given cycle temperature ratio, i. e. Turbine Inlet-temperature/Compressor-Inlet temperature, a modified "Steepest Ascent" routine will rapidly converge to the optimum pressure ratios for the following: maximum thermodynamic efficiency, minimum radiator area, and minimum overall system mass. Of course performance tables as a function of user specified pressure ratios can also be generated, but having the optimum values available has proven to enhance system analysis procedures drastically.

OPEN CYCLE GAS TURBINE PERFORMANCE - Modification of the "Closed Cycle" version of BRMAPS to an open cycle version suitable for both aircraft and automotive Hybrid (prime mover, motor/generator,energy storage) engine applications has been completed. The working fluid for this application is a mixture of air and hydrocarbon fuel combustion products, the properties of which are obtained by execution of the NASA Lewis developed CETPC code (Chemical Equilibrium Code - PC version), as described in reference 6.

Moreover, the heat rejection space radiator routines was omitted for the open cycle version, thus reducing the number of computations.

With the modifications referred to above having been carried out, the thermodynamic performance portion of the code for automotive gas turbine applications is now operational. Development work still needs to be performed for incorporating component weight and volume models specifically for automotive gas turbine engines in a hybrid configuration (i.e., with an energy storage system).

AUTOMOTIVE GAS TURBINE PERFORMANCE ANALYSIS PROCEDURE - The schematic and the corresponding Temperature-Entropy (T-S) diagrams for the open cycle gas turbine engine are shown in figures 1 (a) and (b). As shown by the numbered state points in the schematic, figure 1(a), the main components for executing the Brayton cycle by use of a gas turbine are: A Compressor (1-2); a Regenerator (2-3, and 5-6); a combustor, or external heat addition device (3-4); a Turbine (4-5), producing output work, "W", and also driving the compressor by means of a common connecting shaft. Although in real applications the turbine may be split into two stages, with a high pressure stage driving the compressor, and a low pressure stage driving the load, i.e., a generator, by means of a second shaft, the basic thermodynamic model and performance analysis method is the same. Hence the T-S diagram of figure 1(b) is valid for this case also.

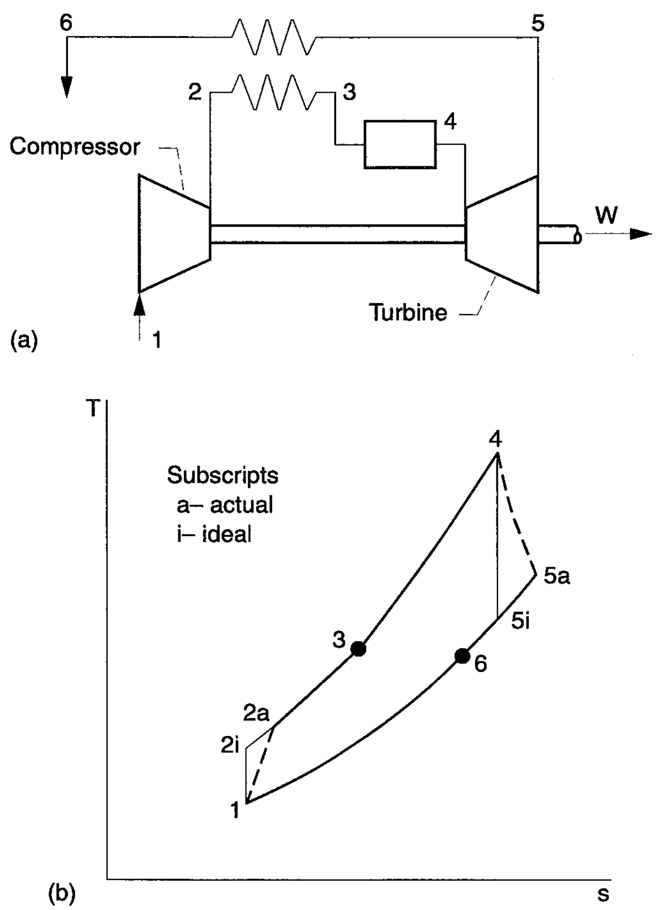

Figure 1.—Open cycle gas turbine diagrams. (a) Schematic. (b) Temperature-entropy.

ESSENTIAL COMPUTATIONS - The main gas turbine steady state performance parameters of interest for automotive applications, i.e. specific fuel consumption and fuel economy, can be derived from the cycle **thermal efficiency** η**,** a dimensionless ratio expressing the amount of cycle work output (Joules or ft-lbs), or work output rate (watts or HP), for a unit amount of heat input, or heat input rate, with units identical to those shown above. **Specific fuel consumption**, expressed in lbs/HP-hr in English units, is a good indicator of engine performance, while **fuel economy**, in miles per gallon, is a measure of combined engine and vehicle performance under standard operating conditions, such as the "metropolitan", or "highway" driving cycle. Note that parameters of interest for automotive applications are given in English units, but actual code calculations are executed using SI units in a user transparent manner.

THERMAL (THERMODYNAMIC) EFFICIENCY OF CYCLE - Based on the diagrams of figure 1, with component performance efficiencies for the compressor, η_c; turbine, η_t; combustor, η_b; and regenerator effectiveness, e_R; the thermodynamic efficiency, η_{th}, of the cycle can be expressed as:

$$\eta_{th} = \frac{\eta_b \dfrac{\Theta_t - 1}{\Theta_c}\left(\alpha\eta_t - \Theta_c/\eta_c\right)}{\alpha\left(1 - e_R + e_R\eta_t - \dfrac{e_R\eta_t}{\Theta_t}\right) - 1 + e_R + \dfrac{1}{\eta_c}\left(1 - \Theta_c + e_R\Theta_c - e_R\right)} \tag{1}$$

where α is the cycle temperature ratio, i.e. T_4/T_1, and with

γ being the specific heat ratio of the working fluid. Since this parameter is a function of temperature and gas composition, γ values for the compressor and turbine will be different, i.e. lower for the turbine.

Θ_c is the compressor pressure ratio parameter, $(p_2/p_1)^{\gamma-1/\gamma}$

Θ_t is the turbine pressure ratio parameter, $(p_4/p_5)^{\gamma-1/\gamma}$

Note that equation (1) does account for duct and regenerator pressure losses by keeping track of compressor and turbine pressure ratios. In the computational model it is convenient to use the ratio $(p_4/p_5)/(p_2/p_1)$, referred to as the "Loss Pressure Ratio", as shown in the "Computer Code Input/Output Parameters" section of this paper.

It should also be pointed out, that equation (1) is applied iteratively with decreasingly smaller step sizes on compressor pressure ratio, in determining the pressure ratio that will yield maximum thermal efficiency. Of course, the code will also evaluate performance directly for user supplied compressor pressure ratios.

SPECIFIC FUEL CONSUMPTION - With the cycle thermal efficiency, η_{th}, thus known, the specific fuel consumption, SFC, can be readily determined from the simple relation

$$SFC = \frac{2545}{\eta_{TH} LHV} \qquad (2)$$

where LHV is the fuel lower heating value.

FUEL ECONOMY - The fuel economy, in miles per gallon (mpg) can be obtained from a knowledge of SFC, fuel specific gravity, SPGRF, the weight of the vehicle, W_{veh}, and the work required to move a standard vehicle over a standard one mile level course at a prescribed speed. A preliminary estimate for this work has been set at 0.389 HP-hr. Using the appropriate conversions, fuel economy can thus be computed as

$$MPG = \frac{(SPGRF * 62.4/7.4813) * (3330/W_{veh})}{(SFC * 0.389)} \qquad (3)$$

COMPUTER CODE INPUT/OUTPUT PARAMETERS - The **input variables** required to execute system performance computations, including state point temperatures, are:

Cycle temperature ratio (ALFA) - This value is identical to the ratio of TIT/TIC, where

TIT - is the turbine inlet absolute temperature (K)

TIC - is the compressor inlet absolute temperature (K)

Compressor pressure ratio (PRC) - If specified as 1, the code will compute performance for the pressure ratio at which the thermal efficiency is maximum for the given ALFA. If a string of values is specified, the code will compute performance for the pressure ratio at which thermal efficiency is maximized and also for each of the pressure ratio values specified.

Combustion Efficiency (ETAB) - The efficiency at which the chemical energy in the fuel (Lower Heating Value) is converted into thermal energy

Fuel Lower Heating Value (LHV) - Default Value is 18,600 BTU/lb

Fuel Specific Gravity (SPGRF) - Default value is 0.8

Compressor Polytropic Efficiency (ETAPC) - Also referred to as infinitesimal compressor stage efficiency. This value together with the specific heat ratio of the working fluid, GAMMA, and the pressure ratio yields the is isentropic compressor efficiency, needed to compute the compressor work. Alternately, the isentropic efficiency can be obtained from a compressor performance map, which shows efficiency contours on a plot of pressure ratio as function of corrected flow for various compressor speed settings.

Turbine Polytopic Efficiency (ETAPT) - Also referred to as infinitesimal turbine stage efficiency. This value together with the specific heat ratio of the working fluid, GAMMA, and the pressure ratio yields the isentropic turbine efficiency, needed to compute the turbine work. Alternately, the isentropic efficiency can be obtained from a turbine performance map, which shows efficiency contours on a plot of pressure ratio as function of corrected flow for various speed settings.

Recuperator (Regenerator) Effectiveness (ERG) - A fractional figure of merit between zero and unity indicative of how well heat is transferred from the high temperature low pressure turbine exit stream to the lower temperature high pressure compressor exit stream before it enters the combustor (also referred to as burner). Note that a value of zero indicates a non-regenerated cycle.

Loss Pressure Ratio (LPC) - The ratio of turbine-to-compressor pressure ratios, reflecting the duct and regenerator pressure losses.

Working Fluid Specific Heat Ratio (GAMMA)- A value above 1 and below 1.666, depending on composition, temperature and pressure of the working fluid. For fluids composed of com bustion products of light hydrocarbon fuels in air, the value of GAMMA will be between 1.3 and 1.4.

Alternator Efficiency (ETM) - The efficiency of conversion of shaft input power to electrical output power available at the alternator power output terminals. This value includes bearing and windage losses and also electrical losses, such as I^2R and losses due to power conditioning and control.

Output Power Level (KWE) - The electrical power output in kW

Vehicle Weight (VEHWT) - Vehicle weight (lbs) for estimating fuel economy in MPG. Default value is 3000 lbs.

It should be noted, that of the above described input variables all do not have to be redefined (read in) for each computer run. Since all input values are stored in a saved workspace, only those parameters need to be varied, the effect of which on overall system performance a user wants to study. For example, the effect of higher turbine inlet temperature could be ascertained by changing ALFA, and the - effect of regenerator performance (effectiveness and pressure loss) could be evaluated by changing the **ERG** and **LPC** parameters.

CODE OUTPUT - The output results, (tables 1 and 2), are printed on a format that shows all key input parameters and their assigned numerical values on the top three lines of the output sheet.

The next line shows the **optimum pressure ratio** values for maximum thermal efficiency. -The values shown for minimum radiator area and mass are not applicable to open cycle power systems. But once empirical **weight models** are developed for the automotive gas turbine components, the mass result calculations can be reactivated. In addition, component and overall volume model output may be added in future editions of the code.-

The last value shown on this line, **TIC-K**, refers to the Compressor inlet temperature, in degrees K.

The line starting with "PR RATIO" is the header line for tabulated output results for values of **compressor pressure ratio**, which is shown in the first column. For this column, the values of the first row are returned by the code as representing the results for the pressure ratio at which thermal efficiency is maximized.

These "result" values, shown in columns 2 to 11 are as follows:

Column number	Designation	Explanation
2	thermal efficiency	Cycle thermodynamic efficiency fractional value. Range 0 to 1.00 (theoretical ideal)
3	SFC	Specific Fuel Consumption in lb/Hp-hr
4	MPG	Fuel Economy in miles per gallon
5	WDT (KG/S)	Working Fluid Flowrate in kilograms/sec
6	TQIN	Combustor Inlet Gas Temperature (K). (T3 in fig. 1(a))
7	TREJ	Exhaust Gas Temperature (K). (T6 in fig. 1(a))
8	TOC	Compressor Exit Temperature (K)
9	TOT	Turbine Exit Tempeature (K)
10	ETAC	Compressor Isentropic Efficiency
11	ETAT	Turbine Isentropic Efficiency

DISCUSSION OF SAMPLE OUTPUT RESULTS - With the output variable names as described above, typical output listings are shown in Tables 1 and 2. In Table 1 the output is shown for a turbine inlet temperature (TIT) of 1100 K (1540 F). With the compressor inlet temperature (TIC) at 293 K (68 F), the cycle temperature ratio is 3.75. Note that output for two user supplied pressure ratios, namely 2.0 and 3.0, was requested. The code first returns the output values for the optimum pressure ratio, 2.38, and the output for the requested ratios is shown on the next two lines. -There is no limit as to the number of lines thus displayed.- In Table 2 the TIT has been increased to 1500 K (2240 F), while the TIC was left unchanged.

The higher cycle temperature ratio now results in significantly increased thermal efficiency and MPG. Note also, that the pressure ratio for maximum efficiency has increased to near 3.0, (2.98), albeit the efficiency at PR=2 is only about 2 percent lower. It should also be noted, that the mass flow rate requirement at the higher temperature ratio has decreased by about 50 percent, even though the output power of 25 kW_e has been maintained. This implies that besides higher efficiency, smaller turbomachinery and ducting are additional dividends resulting from higher turbine inlet temperature operation.

TABLE 1.—AUTOMOTIVE GAS TURBINE CODE—SAMPLE OUTPUT

Brayton Cycle Calculations—Regenerated Cycle—Power Level 25.00 kWe									
Temperature ratio	ETAB	ETAPC	ETAPT	ERG	GAMMA	LPC	ETM	VEHWT, lb	TIT-K
3.754	0.990	0.820	0.850	0.950	1.350	0.950	0.900	4000	1100
Optimum pressure ratios (maximum thermal efficiency; minimum ARP, mass) = 2.380; 2.000; 2.000; TIC-K = 293									

PR ratio	thermal efficiency	SPC, lb/hp-hr	MPG, met-hwy	WDT, kg/s	TQIN	TREJ	TOC	TOT	ETAC	ETAT
2.3800	0.3290	0.4072	39.3972	0.3487	909.74	413.01	385.42	937.34	0.799	0.862
2.0000	.3241	.4133	38.8124	.4199	939.62	395.05	364.79	969.87	.803	.859
3.0000	.3223	.4156	38.5974	.2966	871.67	438.74	414.69	895.72	.793	.865

TABLE 2.—AUTOMOTIVE GAS TURBINE CODE—SAMPLE OUTPUT FOR INCREASED TIT

Brayton Cycle Calculations—Regenerated Cycle—Power Level 25.00 kWe									
Temperature ratio	ETAB	ETAPC	ETAPT	ERG	GAMMA	LPC	ETM	VEHWT, lb	TIT-K
5.119	0.990	0.820	0.850	0.950	1.350	0.950	0.900	4000	1500
Optimum pressure ratios (maximum thermal efficiency; minimum ARP, mass) = 2.980; 2.000; 2.000; TIC-K = 293									

PR ratio thermal efficiency		SPC, lb/hp-hr	MPG, met-hwy	WDT, kg/s	TQIN	TREJ	TOC	TOT	ETAC	ETAT
2.9800	0.4383	0.3056	52.4908	0.1569	1182.58	454.27	413.81	1223.04	0.794	0.865
2.0000	.4178	.3206	50.0320	.2319	1274.66	412.68	364.79	1322.55	.803	.859
3.0000	.4383	.3056	52.4907	.1562	1181.10	455.02	414.69	1221.44	.793	.865

SUMMARY AND CONCLUSIONS

The current implementation of the "Open Cycle Version" of the NASA LeRC BRMAPS Code can be used to run performance comparisons for automotive gas turbine/hybrid engines at steady state opera-ting conditions. The payoff in fuel economy as function of either component improve-ments, or higher turbine inlet temperatures enabled by use of advanced materials, can be rapidly ascertained in order to guide engine development along a most efficient and productive path. Future code enhancements incorporating weight, volume, and perhaps even cost models, may enhance this process even more dramatically.

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