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Practice-Relevant Teaching of Gas Turbine Performance

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ABSTRACT

Gas turbine performance needs to be taught with a clear focus on its practical applications. When teaching this subject, it is tempting to start with the simplest gas turbine configuration - the turbojet. However, this type of engine has not been relevant to aircraft propulsion for many decades. The two-spool turboshaft engines used in helicopters are much more pertinent. The theory of their gas generator is applicable to the most common jet engine, the turbofan.

In practical performance work, the use of computer programs is currently standard; nobody uses the equations usually taught at university, even though they must be covered in introductory courses. Many versions of these are not applicable to modern high-temperature, high-pressure ratio engines, and their superficial use can lead to erroneous conclusions. Equations with constant isentropic exponents or those which neglect dissociation in combustion calculations or heat soakage in transient simulation are examples. Extensive exercises with oversimplified correlations should be discouraged.

However, the use of software has its own challenges because it is perceived by newcomers merely as a black box. One goal of teaching should be de-mystifying the black box, using the software in a targeted way, asking the right questions, checking the results for plausibility, and recognizing incorrect or dubious results.

Specialized gas turbine performance programs, developed at universities or commercially, can be of great help if they go beyond presenting numbers. The results of parametric studies, presented in eye-catching graphs, can tell a lot more about what is important. Temperature and enthalpy - entropy diagrams that are true to scale are helpful. In addition, Sankey diagrams, used to visualize the flow of energy in an engine, can illustrate the results of design and off-design studies very effectively.

INTRODUCTION

Gas turbine performance should be taught with a clear focus on practical applications. It is tempting to start with the simplest jet engine - the turbojet. This type of engine was used in the 1950s in the first jet-powered passenger aircraft such as the de Havilland Comet 2 (Rolls Royce Avon), and early versions of the Boeing 707 and the Douglas DC-8 (Pratt &Whitney JT3C). The turbojet has played no role in commercial aviation since the 1960s, with the exception of the Concorde (Rolls Royce Olympus). For today's typical cruise conditions of 36000ft/Mach 0.85, turbojets are no longer an option for powering passenger aircraft.

Simple turbojets are practically only used today to power cruise missiles flying at about Mach 0.6 at 20000ft, and fighter aircraft capable of flying faster than Mach 2. In both cases, the compressor pressure ratio is limited to modest values, for various reasons. There is no point in spending a lot of time teaching turbojet performance optimization using equations. It is far more important to understand the performance of the gas generator, which is the heart of all gas turbines used for aircraft propulsion.

Many textbooks such as Flack (2023) and Farokhi (2014) that deal with gas turbine performance devote many pages to equations that can be used to optimize the efficiency and specific power of a turbojet. Today, however, everyone has a desktop or laptop computer, and the use of computer programs is standard. No one uses equations for industrial work. An important teaching task now is the demystification of gas turbine performance programs like NPSS, PROOSIS, GSP and

GasTurb. These sometimes have a reputation for being "black boxes" that are impenetrable to the average user. It is the task of the university to lift the veil and make the software transparent to the user.

First, the structure of the performance program should be explained. Students should realize that the individual elements of the program are very simple, and that's why we refer to them as being 0-D performance programs.

A graphical user interface is especially helpful for beginners and occasional users. Simply displaying numbers is not enough. Graphics have a much greater impact, and a variety of viewing options are essential for quick interpretation of results.

In addition to general x-y diagrams, special illustrations of the secondary air system and drawings showing changes of state from one thermodynamic station to another are helpful. True-to-scale enthalpy-entropy diagrams should not be underestimated for understanding the thermodynamic cycle, and energy flow diagrams (Sankey diagrams) are useful as well. Displaying operating points in compressor and turbine maps is essential for interpreting off-design results.

METHODOLOGY

In this paper, the gas generator will be used in place of a turbojet to introduce gas turbine performance. This type of turbomachine consists of the same components as a turbojet, but unlike the latter, it is relevant in practice. A gas generator is the core of many different engines, such as helicopter engines, turboprops, turbofans and turboshafts for generating electric power.

In fact, discussing the performance of a gas generator is simpler than that of a turbojet, since we do need to consider neither the flight conditions in terms of altitude and Mach number, the intake and the exhaust nozzle (convergent versus convergent-divergent nozzle), nor thrust computation

Ideal cycles are irrelevant in practice, so we also ignore those. Lossless compressors or turbines do not exist, so we do our introductory studies with polytropic efficiencies of 90%. Modern combustor efficiencies are close to 100% due to emission requirements, so we likewise neglect losses due to incomplete combustion.

Thermal efficiency and specific power

The main parameters in the cycle of a gas generator are the compressor pressure ratio P_3/P_2 and the combustor exit temperature T_4. The primary assessment criteria for a cycle are the thermal efficiency η_{th} and the isentropic specific power ΔH (in kW/(kg/s)).

First, we compare the results of different calculation models and start by evaluating simple formulas as found in textbooks. The thermal efficiency of a gas generator can be calculated using the following equation:

$$\eta_{th} = \frac{\Delta H_T - \Delta H_C}{\Delta H_B} = \frac{c_{p,T}(T_4 - T_5) - c_{p,C}(T_3 - T_2)}{c_{p,B}(T_4 - T_3)} \tag{1}$$

This equation can be expanded to:

$$\eta_{th} = \frac{\frac{\gamma_T}{\gamma_T - 1} * R_T * \frac{T_4}{T_2} * \left[1 - \left(\frac{P_2}{P_3}\right)^{\frac{\gamma_T - 1}{\gamma_T}}\right] * \eta_T - \frac{\gamma_C}{\gamma_C - 1} * R_C * \left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma_C - 1}{\gamma_C}} - 1\right] \Big/ \eta_C}{\left(\frac{T_4}{T_2} - \frac{T_3}{T_2}\right) * \left(\frac{\gamma_C}{\gamma_C - 1} * R_C + \frac{\gamma_T}{\gamma_T - 1} * R_T\right)/2} \tag{2}$$

In the simplest form - which is often used for teaching purposes - it is assumed that the isentropic exponent γ, the gas constant R and thus specific heat $c_p = \gamma/(\gamma-1)*R$ are constants.

Figure 1 illustrates the results of equation 2 over an extremely large (and unrealistic) range of pressure ratios. The temperature range at a given pressure ratio is implicitly given in this figure by the range of equivalence ratios from 0.1 to 1 for a typical hydrocarbon fuel. The isentropic compressor and turbine efficiencies are calculated from given polytropic efficiency of 0.9.

The goal of this exercise is to answer the question: Is there an optimum of thermal efficiency anywhere? The answer is no - at least not in the range of the parameters under investigation. Another finding is that with constant isentropic exponent γ one gets a significantly different result than if one considers the dependence of γ on temperature and air-fuel ratio. In fact, the result for the constant γ is misleading because it says that the highest burner exit temperature gives the highest thermal efficiency. This is obviously not the case, as can be seen in the figure on the right, which takes into account the temperature dependence of γ.

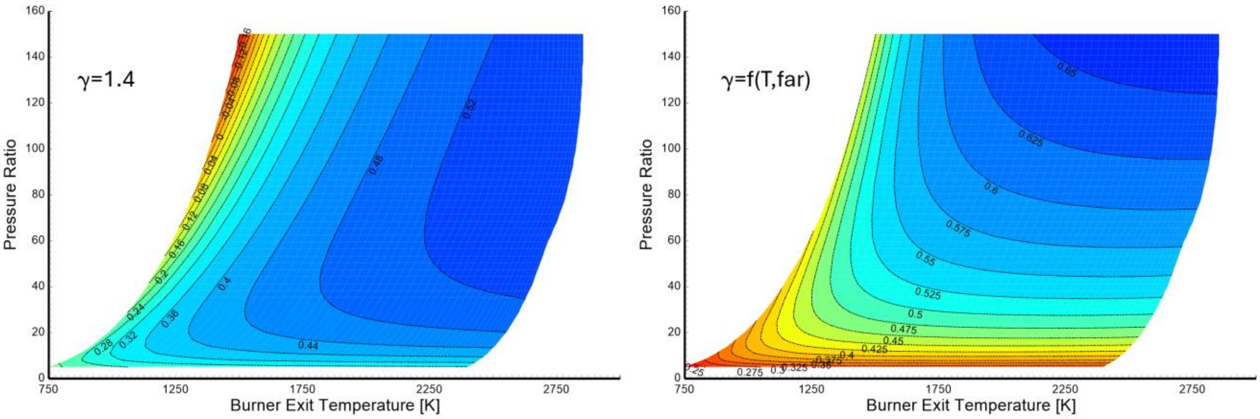

Figure 1: Thermal Efficiency Calculated With eq. 2 for Constant γ (left) and γ = f(T,far) (right)

The next figure shows results for thermal efficiency calculated with the GasTurb software first published by Kurzke (1995). The decisive difference between Figures 1 and 2 is how thermal efficiency is defined. In equation 1 the added heat is calculated as an enthalpy difference of the gas, while in GasTurb the added heat is calculated as product of fuel flow and fuel heating value. The amount of fuel needed for a certain temperature difference T_4-T_3 is read from tables created with the NASA CEA program published by Gordon and McBride (1994, 1996).

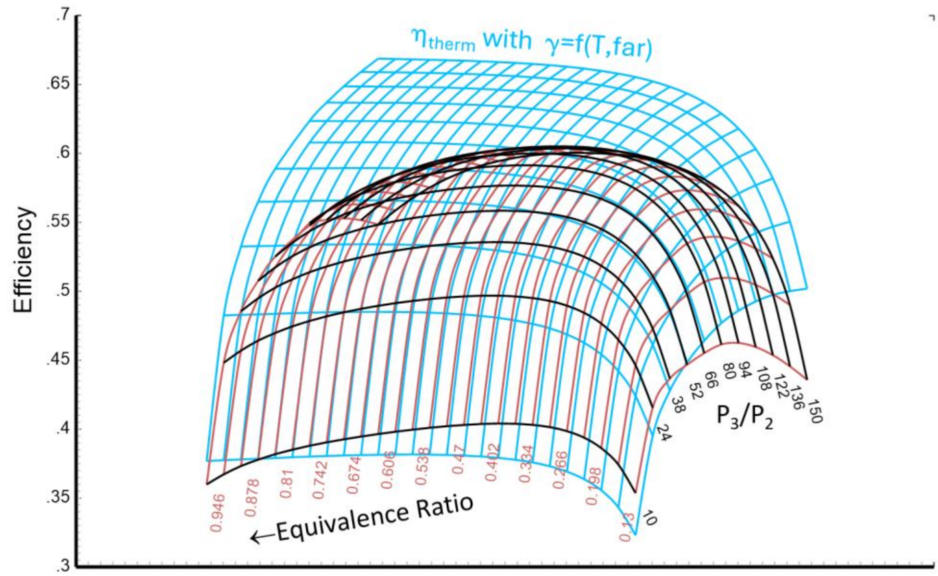

Figure 2: Thermal Efficiency = f(Equivalence Ratio and Pressure Ratio)

The black/red carpet in Figure 2 shows an optimum for thermal efficiency at an equivalence ratio of about 0.5, while Equation 2 (the blue carpet) ignores the limits of what can be achieved by burning hydrocarbon fuels. It is obvious that any cycle optimization based on Equation 2 gives an unrealistic answer, not only in terms of achievable thermal efficiencies, but also leads to the fundamentally incorrect conclusion that stoichiometric combustion would give the highest thermal efficiency.

The left side of Figure 3 shows the efficiency values from the black/red carpet in Figure 2 in the same format as Figure 1. The optimal thermal efficiency occurs at a pressure ratio of about 120. The reason for this result is the neglect of the necessary turbine cooling. For the calculation of the right-side of Figure 3, the amount of cooling air required for a given metal temperature of the turbine blade was taken into account. In the simple correlation described by Kurzke (1995), both the temperature of the mainstream gas and that of the cooling air (compressor outlet temperature T_3) are considered.

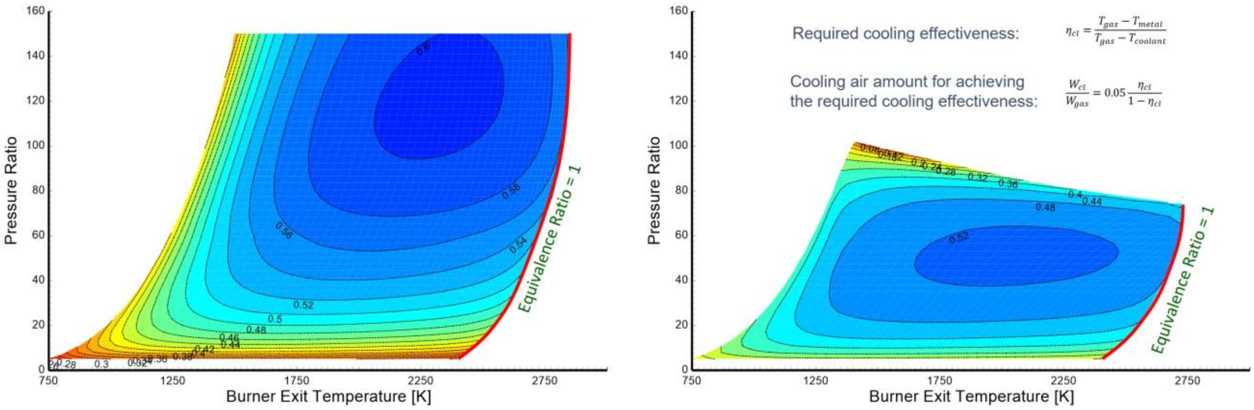

Figure 3: Results from a Performance Program Without and With Cooling Air Simulation

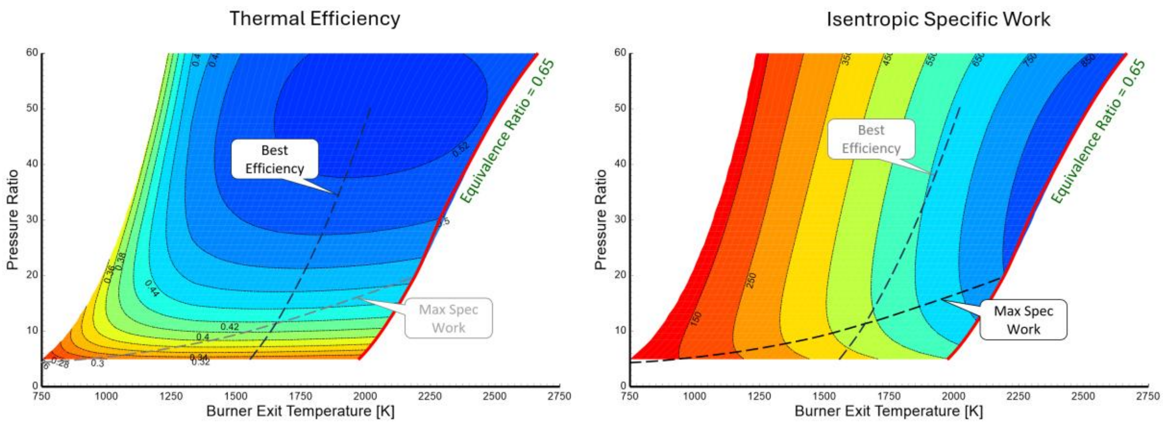

Figure 4: Design Space for a Gas Generator

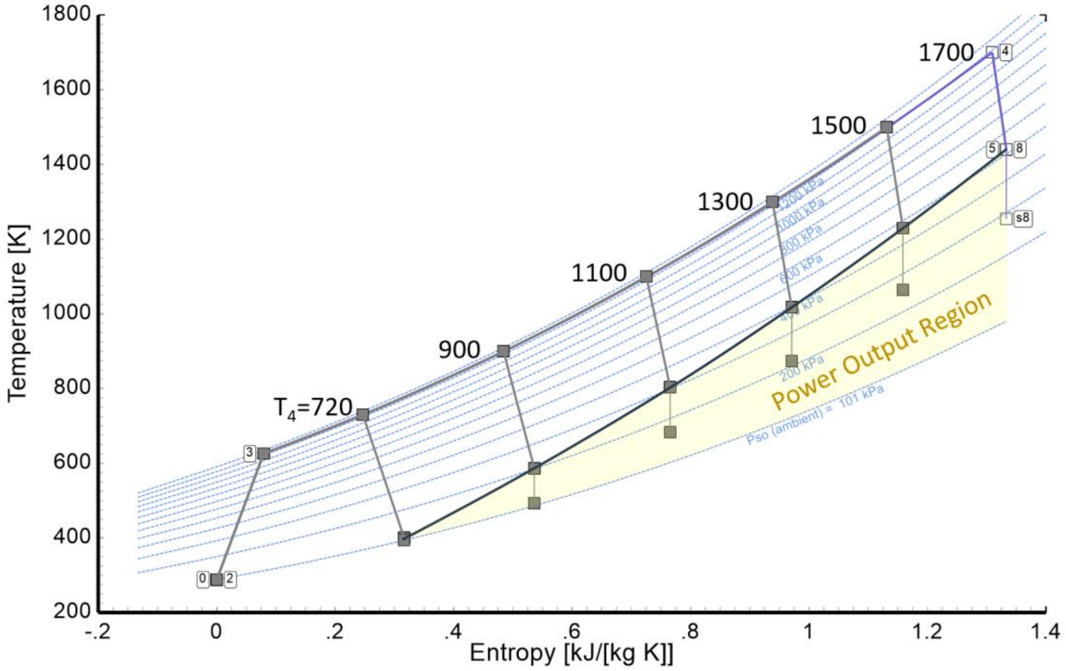

Figure 5: Increasing T_4 Yields More Power

The pressure ratios of up to 150 considered in Figures 1 and 2 have nothing in common with those of real gas turbines. Figure 3 illustrates that stoichiometric combustion does not result in the highest thermal efficiency. Therefore, in Figure 4 we consider a limited design space that is more realistic. The upper border for pressure ratio is 60, and the right boundary is 65% of the stoichiometric fuel-air-ratio. There we also add the second important performance parameter, the specific power in kJ/(kg s) at the gas generator exit.

The left side of Figure 4 is a detail magnification of the right side of Figure 3. It contains two dashed lines which denote the respective paths to high efficiency and high specific power. The power can be used either directly to generate thrust (in which case we get a turbojet) or indirectly to drive a low-pressure turbine, which powers the rotor of a helicopter, a propeller, the fan of a turbofan or an electric generator.

The general message regarding specific power is that, at any given pressure ratio, the highest temperature gives the highest power. How can this be explained? The answer is: by looking at the temperature-entropy diagram. A single T-S diagram does not provide much insight, but comparing the diagrams of two or more cycles tells an easy-to-understand story. Figure 5 shows the thermodynamic cycles for six burner outlet temperatures for the same compressor pressure ratio, starting with T_4=720K. At this low temperature, the turbine needs all the available pressure ratio P_4/P_{amb} to generate the power required by the compressor. With T_4=720K, there is no pressure ratio left to drive a low-pressure turbine. At T_4=900K, there is some energy left after the gas generator to accelerate the flow in the nozzle of a turbojet to sonic speed, for example. It is quite obvious and easy to remember: higher temperatures produce higher nozzle pressure ratios and there is a direct correlation between T_4 and P_5/P_{amb}.

The T-S diagram provides a clear representation of this phenomenon; the derivation of complex equations and application of optimization algorithms are not required. Drawing T-S or H-S diagrams to scale to compare cycles is a very valuable tool for teaching gas turbine performance. The entire cycle can be seen at a glance. The old saying still applies: A picture is worth a thousand words. If your performance software does not yet allow you to draw T-S diagrams to scale: add this feature!

Performance Calculation Software

Practice-relevant teaching means not only dealing with practice-relevant problems but also introducing the tools used for performance work in practice. Until the 1980s, there were slide rules and pocket calculators; in the 21st century, there is software such as NPSS, PROOSIS, GSP, GasTurb, etc. Some universities have developed their own software as, for example, Mathioudakis et al. (1999 and 2002), Pontika et al. (2019), Apostolidis et al. (2013) and Tsentis et al. (2024). Obviously, knowledge about this sort of software must be part of a performance engineer's education.

Physics

Gas turbine performance calculation programs differ from those of computational fluid dynamics (CFD) and finite element analysis (FEA) in one important aspect: their output can be easily reproduced on a pocket computer or in Excel. Doing that is not just an academic exercise, but often necessary in practical engineering when partners in a collaborative project arrive at different results because they are not using the same software or are making different assumptions.

The recalculation of a simple turbojet cycle as described by Kurzke et al. (2025) is suitable for beginners with little prior knowledge. The figures from the cited book should not be used in students' exercises directly, as this would be too simple. Change the requirements and assumptions a bit to make the task more challenging. Finally, compare the hand-calculated numbers with the results of your preferred performance software. The differences between the results of the two calculations must be very small, and if they are not, then something is wrong.

One problem with the Excel calculations is the modeling of the gas properties, which requires the use of high-order polynomials, such as those published by Walsh and Fletcher (1998). The use of these polynomials makes the exact calculation of simple compression and expansion methods with Excel quite complex. One way out of this dilemma is to use the GasTurb Details program, which provides a set of procedures for calculating gas turbine component performance that are consistent with the procedures used in GasTurb. With this utility, one can examine component performance in more detail than with the full cycle program. Examples are the flow phenomena in a convergent-divergent nozzle (under expanded, overexpanded, shock in the divergent section, subsonic flow) and the mixing of the bypass with the core flow.

The manual calculation of an arbitrary cycle is intended to give students confidence in the software. A subsequent exercise could be to recalculate the cycle of an existing engine. This is much more challenging than the first exercise, but also more exciting. Will the student be able to reconcile his model with the known data such as pressure ratio, mass flow, bypass ratio, and SFC? If more than one student is doing the exercise, who will come up with the most plausible model?

Once students are able to reproduce the thermodynamic cycle with credible assumptions for component efficiencies, pressure ratios, and turbine inlet temperature, they can dig a little deeper and try to reproduce the geometry of an engine. This will require more than just the total temperatures and pressures that define the thermodynamic cycle. To create the geometry model, one needs to know also the static quantities, the local Mach numbers, and the flow annulus areas at the thermodynamic stations. Figure 6 shows these and some other interesting properties of the CFM56-3 turbofan geometry model depicted in Figure 7 (for numbers see Kurzke et.al. (2025).

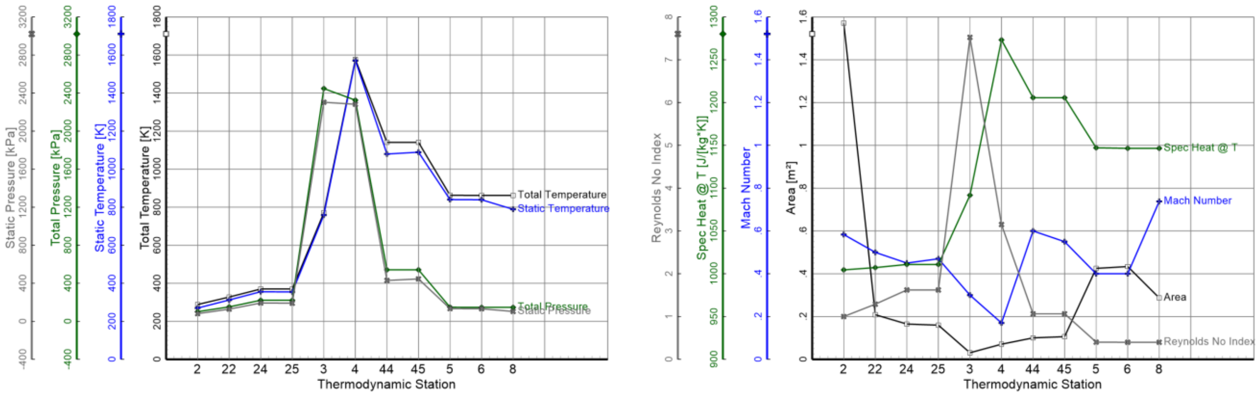

Figure 6: Cycle Data of the CFM56-3 Turbofan

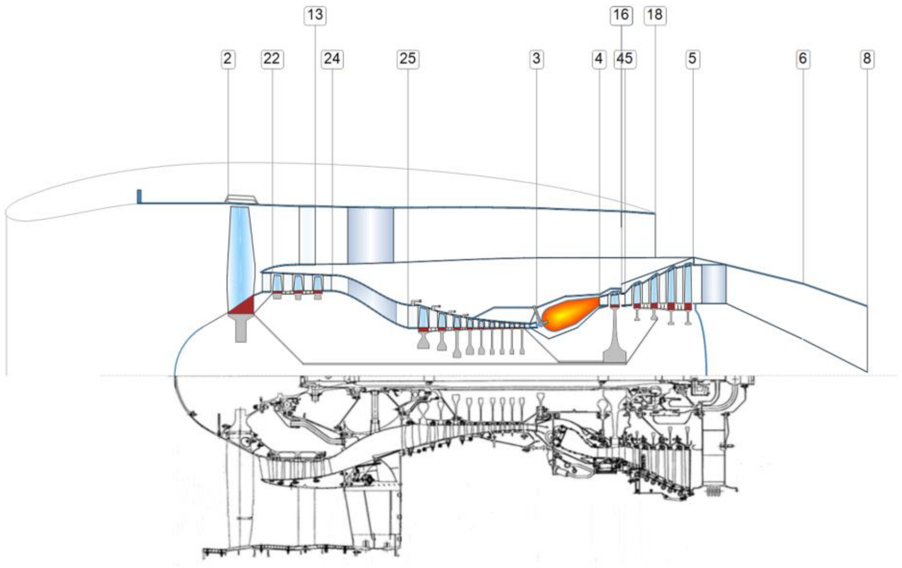

Figure 7: Geometry Model of the CFM56-3 Turbofan

Another interesting exercise for students would be to generate an engine cycle that meets an SFC target propagated in the context of future aviation emissions requirements.

Mathematics

Traditional gas turbine performance software consists of program modules (objects) that describe the physics of compressors, turbines, burners, nozzles, etc. These modules use an accurate description of the working fluid, but not the complex formulas found in textbooks. They are programmed in the simplest way possible. Mathematical algorithms and procedures are used to assemble the program modules into a complete engine model.

Cycle design calculations are generally simple and straightforward. They begin with the intake and proceed through each component until the gases expand to ambient pressure. Turbofans require an iterative approach because an appropriate value for the fan pressure ratio is not known at the start. For a mixed-flow turbofan, the bypass and core exit pressures must be similar, and for a separate-flow turbofan, the ratio of nozzle exit velocities should be reasonable.

Off-design calculations inevitably lead to a multi-dimensional iteration problem. Several unknowns must be estimated and manipulated to resolve any incompatibility in the simulation. The mathematical procedure for this is the so-called Newton-Raphson algorithm. Understanding the principles of this algorithm, its advantages, and its limitations are of paramount importance for every performance engineer.

In a Newton-Raphson iteration, the task is to manipulate a set of variables so that an equal number of errors (number of incompatibilities within the performance model) are less than a specified tolerance. The algorithm begins by computing the Jacobi matrix, which consists of the partial derivatives of how the errors change as the variables change. The Jacobi matrix is then used to calculate how the variables must be changed to make all errors zero.

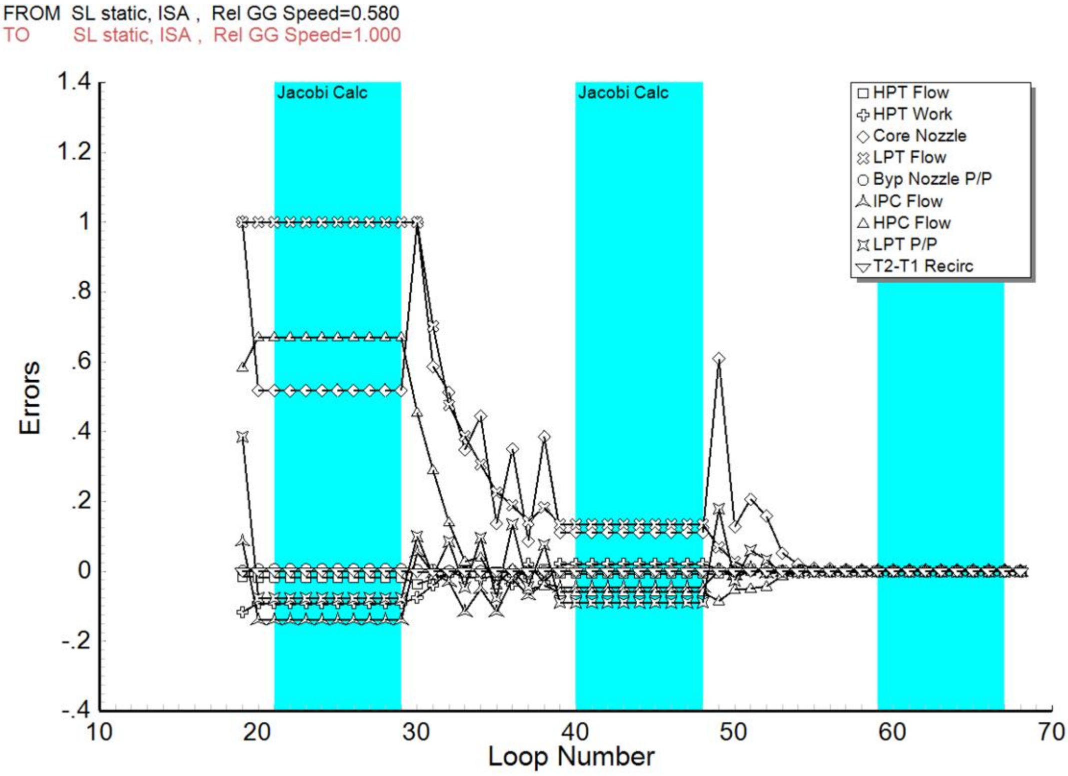

Figure 8: Iteration History Example

The convergence behavior of the Newton-Raphson algorithm is usually quite good, but sometimes no solution is found. Then the question must be answered: why is this the case and what can be done to get convergence? There are two reasons for non-convergence: First, there is a solution, but the algorithm does not find it. Second there is no solution because the problem is unsolvable. This may be a physically impossible combination of requirements (thrust, bleed, power offtake, rpm, T_4, etc.). Looking at the history of the iteration process can be helpful in understanding why convergence is not achieved. Perhaps the limit on the number of iteration loops was too low? Is the specified iteration tolerance too tight? All this can be seen from a graph of the iteration history as shown in Figure 8.

Application

There are two main uses for performance software in the classroom: student practice and lecture preparation. While a good user interface is always desirable, ease of use is especially important for students' exercises. A GUI similar to that of standard software like Word, Excel or Power Point is particularly helpful for beginners and occasional users.

Figures 1, 3 and 4 show the results of academic parametric studies as absolute numbers, which are fairly simple software applications. In reality, comparing results, as shown in Figure 2, is the more important case. Typically, engineers look for differences between alternative solutions to a problem.

Instead of the usual x-y plots, it is advisable to compare thermodynamic cycles in temperature-entropy or enthalpy-entropy diagrams. Figure 9 shows the effect of a 5% change in compressor efficiency for two fundamentally different calculation paths. The left display shows the result of cycle design computations that determine the geometry of engines. There is not much difference between those two cycles since only the compressor and turbine exit conditions are influenced by efficiency.

In the right part of Figure 9 - which shows the result of an off-design calculation (where the engine geometry is known) - the effect of a 5% reduction in compressor efficiency is much greater. Note that the effect also depends on how the engine is controlled. In this example the burner outlet temperature T_4 was kept constant, alternatively one could choose constant thrust or constant spool speed, or constant turbine exit temperature, or...

Graphs like the one in Figure 9 can leave a lasting impression, certainly more than laboriously derived equations. Presenting such results as values in tables would certainly not be very impressive and would quickly be forgotten.

Instructors can use the software to supplement their lecture notes for students. Instead of cartoons, they can create to-scale illustrations that are much more useful. Temperature-entropy and enthalpy-entropy diagrams are very helpful in communicating with an audience because they show the whole thermodynamic cycle, not just a few component details.

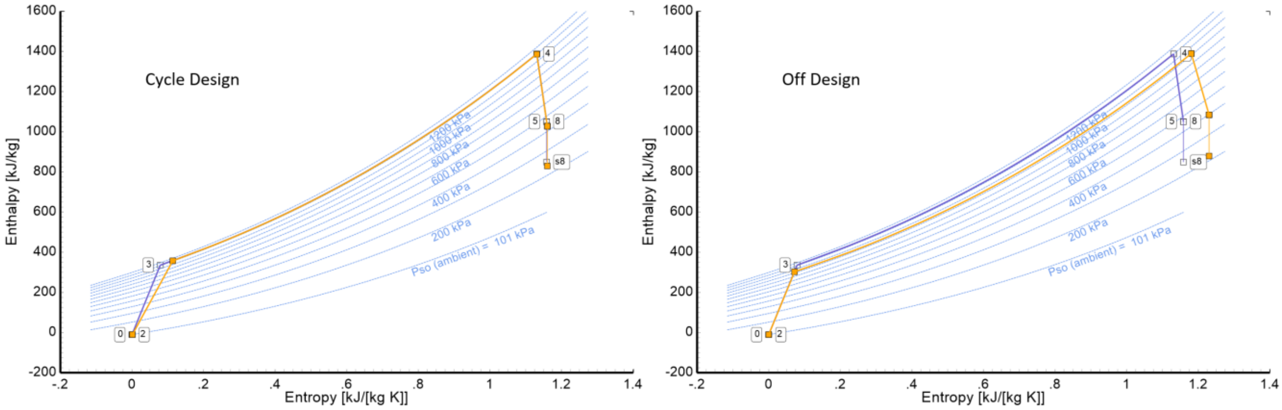

Figure 9: Turbojet Cycle Design and Off-Design Response to $\Delta\eta_{23}$= - 5%

The specific fuel consumption of an engine with an afterburner is more than twice that of an engine without one. Why is that? It is not that the afterburner efficiency is much lower than in the main combustor – and Figure 10 gives the answer!

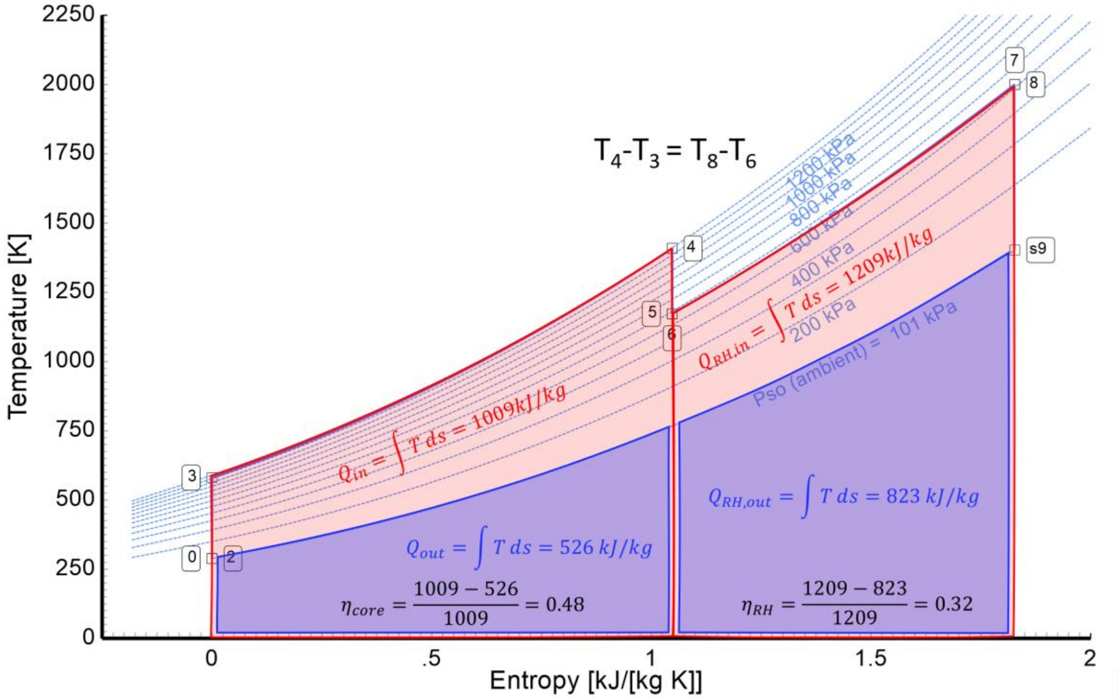

Figure 10: Ideal Cycle of a Reheated Turbojet

The left part of Figure 10 shows the core engine process and the right part shows that of the afterburner. Here, the red areas below lines 3-4 and 5-7 represent the heat added in the combustor and reheat system, respectively. The amounts of heat lost to the environment are represented by the two blue areas. Thermal efficiency is the ratio (Q_{in}-Q_{out})/Q_{in}, and by looking at the colored areas, it is easy to see that the efficiency of the core engine process is significantly higher than the efficiency of the reheat system. The impression from Figure 10 is much more vivid than it would be from an equation.

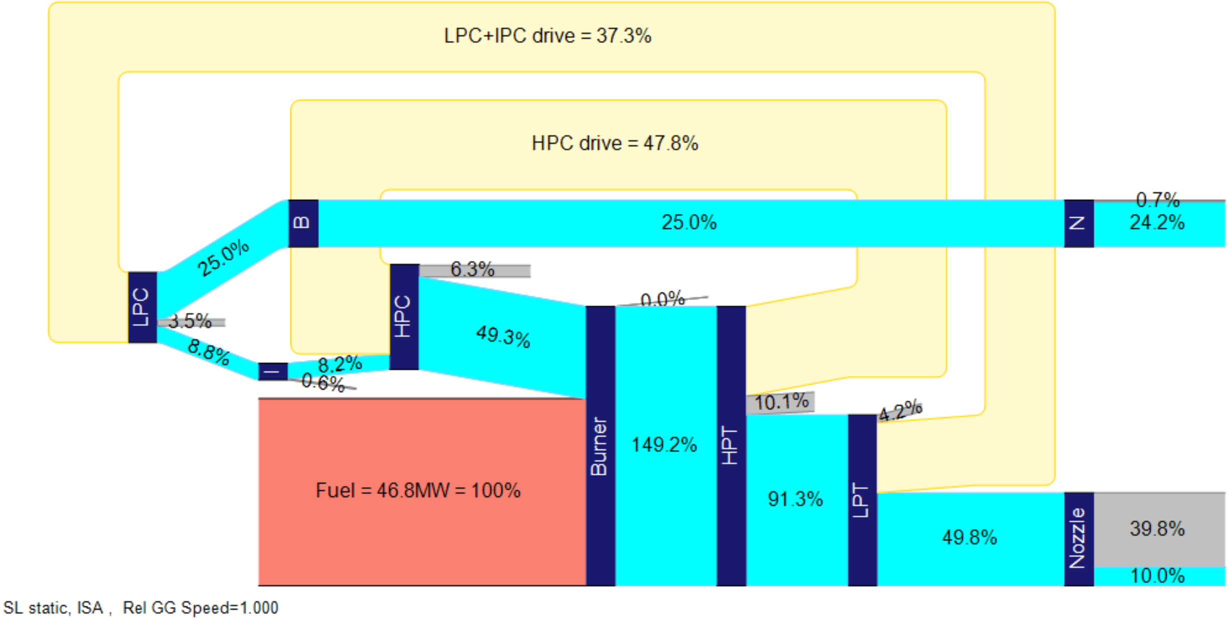

Figure 11: CFM56-3 Sankey Diagram for Take-Off Power

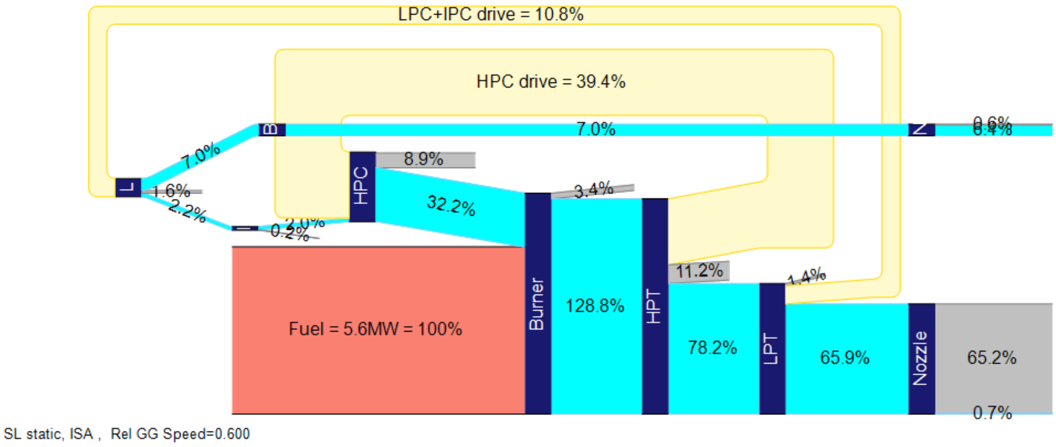

Figure 12: CFM56-3 Sankey Diagram for Idle

Another effective way of presenting results is a Sankey diagram which illustrates the energy flows within an engine. Münzberg (1972) shows and discusses such a diagram for a reheated turbojet. Creating this diagram by hand is quite tedious, but creating one with software is just a click away once you have programmed it. It would be desirable to show not only the main energy flows but also all the secondary energy flows, such as those attributed to cooling air, that absorbed by the accessory gearbox, as well as the effects of air and power offtakes. However, even if only the main energy flows are shown as above, a Sankey diagram is impressive because it shows clearly that the internal energy flows are much greater than the useful kinetic energy produced.

Figure 11 shows the Sankey diagram for the CFM 56-3 for the cycle reference point published in the book of Kurzke et.al. (2025). The diagram illustrates the relative importance of each component. In the cross-sectional drawing (Figure 6), the high-pressure turbine takes up very little space, whereas the fan is geometrically much larger. Figure 11, however, shows that the energy conversion in the HPT is much larger than that in the fan!

Figure 12 shows the Sankey diagram for Idle. The energy of the fuel is only 12% of that at take-off and so the absolute energy flows are much smaller than those in Figure 11. Again, the energy flows in the gas generator are much larger than those of the components on the low-pressure spool.

This closes the circle. The paper began with the statement: the gas generator is the most important component of an engine and practically relevant teaching should focus on it.

CONCLUSIONS

The availability of software to everyone is changing the way gas turbine performance training can best be conducted. The derivation of complex formulas and relationships is no longer relevant for practical work in the industry. Today's task is to demystify the "black box", as the performance program is defamed by some. This cannot be achieved by trial and error and playing around randomly with the software. Recalculating a program result with a pocket computer by hand, one component at a time, is the key to understanding what happens in the software.

It can be argued that the traditional formulas convey the fundamental relationships accurately. However, this is only true to a limited extent because too many simplifying assumptions must be made to derive the equations. Cycle optimization exercises that ignore the temperature dependence of the isentropic exponent and neglect the turbine cooling air are outdated and irrelevant in practice.

Particularly in the case of teaching, it is not about absolute figures for power, thrust and fuel consumption. It is much more important to understand which parameters have an influence on a desired result and why this is the case. Comparisons between different alternatives are the standard task for the performance engineer and how best to do this, what to look for and how to check whether a calculation result is correct at all - these are the questions that are relevant in practice.

NOMENCLATURE

Equivalence Ratio	actual fuel to air ratio divided by stoichiometric fuel to air ratio.	
far	fuel to air ratio	
H, ΔH	enthalpy, enthalpy difference	kJ/kg
P	total pressure	kPa
Q	heat	kJ
R	gas constant	kJ/(kg K)
S	entropy	kJ/(kg K)
T	total temperature	K
W	mass flow	kg/s
γ	isentropic exponent	
η_{th}	thermal efficiency	
η_{cl}	cooling effectiveness	
η_{23}	compressor efficiency	
Indices		
amb	ambient	
B	burner	
C	compressor	
RH	reheat	
T	turbine	
Station No.		
2	compressor inlet	
3	compressor exit	
4	burner exit, turbine inlet	
5	turbine exit	
…others	see fig. 6	

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