

A Teaching Approach for Gas Turbines Using Spreadsheets*

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This paper describes a spreadsheet-based approach for the calculation of the component matching in a gas turbine engine. The spreadsheet solution is based on a classic, graphical method, so it can easily be understood by the student. The student can concentrate his attention on problem fundamentals and the solution, since no calculation effort is needed on his part. The teaching methodology has been satisfactorily used with Mechanical Engineering students, whose feed-back is summarized.

Keywords: Gas turbine engines; power plants; spreadsheet; mechanical engineering

INTRODUCTION

IN THE LAST YEAR of mechanical engineering studies students are instructed in thermal engines. One of these engines is the gas turbine, which is used in many branches of industry.

A gas turbine engine is mainly composed of a compressor, a combustor and a turbine. In previous courses students have gained knowledge about the equivalent thermodynamic cycle of the gas turbine engine (known as the Brayton cycle). They also know about compressor operation flowcharts and elementary turbines, also combustion fundamentals needed for combustor modeling. However, they do not know how the selection of these three elements determines the operating equivalent cycle.

The problem is complex in the sense that, for a given selection of the engine components, the equivalent thermodynamic cycle depends on the operating conditions (usually specified by a pair of variables, such as turbomachinery speed and injected fuel mass). The component-to-component interaction is conceptually simple, but the existence of algebraic loops complicates the resolution of the problem. The selection and interaction of the different elements in a gas turbine is known as the 'matching problem' [1].

There is a classical graphical method that solves the matching problem [1, 2], but students are not familiar with it. However, computer simulation can be used for the matching problem resolution. Although numerical simulation is possible, and the graphical method is based on the assumption of important simplifications, a computer-aided resolution by means of the graphical method has been chosen in order to combine the benefits of both methods and to help students in understanding both the problem and the resolution procedure.

Here we feature a spreadsheet-based solution. Compared with compiled software implementations (which can have friendly graphical user interfaces), the use of spreadsheets allows students to analyze all used formulae; compared with other programming frameworks, such as AmeSim, Matlab/Simulink or Modelica, spreadsheets are quite simple and not much expertise is needed.

Hence, our purpose is twofold:

- 1) To present an alternative way to teach gas turbine engines based on Brayton cycle; in order to maximize 'learning efficiency' [3], combining the visualization advantages of the graphical resolution with the calculation power and simplicity of spreadsheets.
- 2) To present in detail a calculation tool that simplifies the quantitative aspects of the matching problem in Brayton cycle engines, and calculates overall results like engine efficiency and the equivalent thermodynamic cycle for a given operating condition. With this tool it is possible to easily analyze the effect of the different parameters on the behavior of the assembly. Students will be able to trace performance and efficiency maps of the engine taking into account variations in the operating conditions.

This approach is a good illustration for students of how to face design and open-ended engineering problems. The spreadsheet application for engineering problems resolution is being increasingly applied both in the educational and professional world [4–13].

TEACHING APPROACH

The spreadsheet to solve the coupling of a compressor and a turbine in a Brayton cycle engine is used during a practical lesson included

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in the course planning. The reason for being included as a practical lesson is twofold:

- 1) because the use of computers is required
- 2) because of the reduction of class size during practical sessions (20 students compared to standard 100 student group in the theoretical lessons).

The duration of the practical work is three hours.

The first activity during this practical work is to review the main features of compressors and turbines. When all those issues are clear, a discussion on what boundary conditions need to be taken into account when the two elements are coupled is carried out. At this point the students discover the simple relationships that should be considered to solve this problem, and they are requested to perform by hand the calculation of a very simplified case where all processes are idealized. This short exercise will help them to appreciate the potential of the spreadsheet tool, which can perform more complex and accurate calculations automatically.

In a further step, more complex cases are solved via the Excel spreadsheet. The students are not responsible for setting this up from scratch. They are given exactly the right equations from the Excel spreadsheet; and are only required to change several inputs and further to analyze the results. With these results the students can observe realistic trends.

The main changes the students make to the Excel worksheet are:

- Turbine geometrical parameters, such as turbine flow coefficient (effective area), flow angle of the stator blades, number of stages; or loss coefficients like the velocity losses at the stator and rotor.
- Compressor flow chart and compressor efficiency map are also important inputs. Nevertheless, due to the high amount of data required,

the students are provided with several maps to be exchanged in the engine simulation.

- Engine operative parameters, such as turbine inlet temperature and the speed of the turbomachinery assembly in the engine.

One important objective of the analysis activity is to select the optimum turbine size for a given compressor map. Once this has been done, students are required to draw an engine operation map (for power or efficiency). For this purpose different turbine inlet temperatures are exchanged in the spreadsheet as the main input, in order to map the full operation range. Using fuel mass, power (or efficiency) and speed, students can draw contour plots in a plane formed by the fuel mass flow versus the speed of the engine turbomachinery.

The strength of this approach is that, on the one hand, the student understands the easy conceptual basis of the problem because they are not distracted by long and complex calculations or by formulae programming. On the other hand, the trends they can observe are quite realistic due to the adequate selection of the hypothesis, but with not too much mathematical effort from their side (this effort is transferred to the computer). In turn, they are requested to concentrate their efforts on analysis of the results.

INPUT DATA, HYPOTHESES AND EQUATIONS

In order to clarify the nomenclature used in this paper, in Fig. 1 a schematic of the gas turbine layout and the ideal and actual cycle are presented. Subscripts for all variables are referred to the labels indicated in both plots of the figure.

Input data

The different data required as an input to solve the compressor/turbine assembly are:

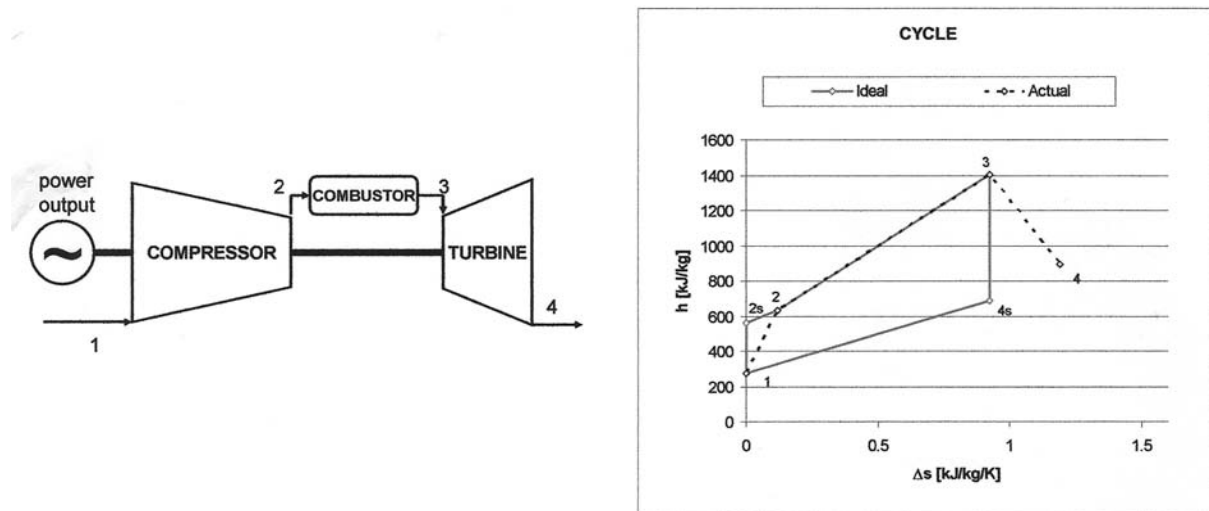


Fig. 1. Schematics of the gas turbine layout (left). Ideal and actual thermodynamic cycle (right).

- Compressor characteristics:
 - A compressor flowchart showing the relationship between compression ratio, π_c , corrected mass flow, \dot{m}^* , and rotor speed, n . An example of such flowchart can be observed in Fig. 1.
 - A flowchart showing the relationship between π_c , \dot{m}^* and compressor isentropic efficiency, η_c . An example of this flowchart is available at Fig. 2.
- Turbine characteristics:
 - Flow coefficient, A_{ef} from Eq (3), to characterize the turbine as an equivalent nozzle.
 - Number of turbine stages, z .
 - Flow angle at the stator blade outlet, α .
 - Coefficient for velocity losses at the turbine rotor and stator, k_w .
- Atmospheric pressure and temperature.
- Working fluid properties: the particular gas constant, R , the specific heating capacity at constant pressure, c_p , and the adiabatic coefficient, γ .
- Fuel heating value, H_p .

In addition, operating conditions, defined as turbomachinery rotating speed and temperature at the turbine inlet, are assumed to be known. Fixing turbine inlet temperature is a usual assumption during the design process as it is limited by the material thermal resistance, and also it is closely related with the air-to-fuel ratio, a key factor for the combustor proper operation.

In fact, the implementation shown in this paper calculates engine behavior for a fix turbine inlet temperature in all the turbine speed range. In addition, the equivalent thermodynamic cycle is solved only for the specified speed (solving it for all the turbine speed range will result in a family of diagrams as the one shown in the right plot of Fig. 1).

Hypotheses

The main hypotheses that allow an easier approach to the problem solution are the following:

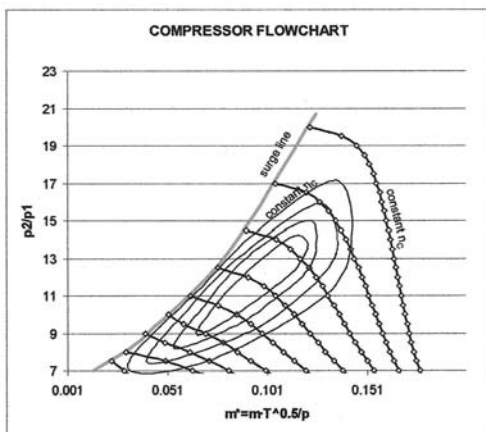


Fig. 2. Compressor flowchart: compression ratio vs. corrected mass flow for several compressor speeds.

- The mechanical efficiency is 100% (no friction losses are considered).
- The combustion is complete, thus all the energy contained in the fuel is released during combustion.
- The working fluid is considered to be always air, which is supposed to behave as a perfect gas.
- The fuel mass is neglected compared to the air mass, consequently the mass flow is supposed to be the same through the compressor as through the turbine. The influence of the fuel mass and enthalpy are neither considered in the combustor.
- The initial conditions are considered to be those of the ambient.
- No pressure losses in the different elements are considered. Thanks to this hypothesis the compression ratio (at the compressor, p_2/p_1) and the expansion ratio (at the turbine, p_3/p_4) are the same.
- Both the compression and the expansion processes are considered to be adiabatic, but not isentropic.
- Kinetic energy at the compressor's and turbine's inlets and outlets are negligible.
- Two simplifications have been done for the turbine flow characteristics: there is no influence of the blade tip velocity on the turbine's swallowing capacity [1], and the first stator is the first element choking along the turbine. Furthermore, choking condition is reached as if the turbine behaves as a single nozzle. In the case of turbines with low number of stages, the turbine is usually choked; hence this last assumption is not of great importance [1]. This simplification was adopted in order to facilitate the analysis of the results, although multistage turbines could be easily programmed.

Most of these simplifications are not mandatory but allow a better understanding of the results.

Equations

Next, governing equations and fundamentals of the three main elements are provided:

- Compressor: compressed air mass flow for a given compression ratio strongly depends on the compressor shaft speed. This dependency is usually represented in a characteristic flowchart, which relates air mass flow corrected by pressure and temperature, shaft speed, and compression ratio. An example of this kind of flowcharts is shown in Figure. 2.

On the other hand, compressor flowchart also represents compression efficiency, which relates required power with the isentropic power:

$$\dot{W}_C = \frac{\dot{W}_{C,s}}{\eta_C} = \frac{\dot{m}_C}{\eta_C} \cdot c_p \cdot T_1 \cdot \left(\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \quad (1)$$

Conditions at the compressor outlet can be calculated as follows:

$$h_1 = c_p \cdot T_1 \quad T_{2s} = T_1 \cdot \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$h_2 = \frac{\dot{W}_C}{\dot{m}_C} + h_1 \quad T_2 = \frac{h_2}{c_p} \quad (2)$$

- Turbine: the turbine is supposed to be an axial multistage unit with z reaction stages.

Instead of a flowchart, theoretical-derived equations are used for the turbine. In the case of the turbine flow, a nozzle equation serves as a good estimation:

$$\dot{m}_T = A_{ef} \cdot \frac{p_3}{\sqrt{R \cdot T_3}} \cdot \phi \left(\frac{p_4}{p_3}\right)$$

$$\phi \left(\frac{p_4}{p_3}\right) = \sqrt{\frac{2\gamma}{\gamma-1} \cdot \left(\left(\min\left(\frac{p_4}{p_3}, k\right) \right)^{\frac{2}{\gamma}} - \left(\min\left(\frac{p_4}{p_3}, k\right) \right)^{\frac{\gamma+1}{\gamma}} \right)} \quad (3)$$

$$k = \left(\frac{\gamma+1}{2}\right)^{\frac{2}{\gamma-1}}$$

Turbine efficiency can be analytically derived from Euler equation for the (reaction) turbomachinery stages, with the addition of loss coefficients in order to consider the friction phenomenon [14]:

$$\eta_T = 2 \cdot \frac{u}{c_s} \cdot \left(k_w \cdot \sqrt{2} \cdot \cos(\alpha) - \frac{u}{c_s} \right) \quad (4)$$

$$u = \frac{2\pi \cdot n}{60 \cdot z} \quad c_s = \sqrt{2 \cdot \frac{c_p \cdot T_3 \cdot \left(1 - \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}}\right)}{z}}$$

Finally turbine power can be calculated as follows:

$$\dot{W}_T = \eta_T \cdot \dot{W}_{T,s} = \eta_T \cdot \dot{m}_T \cdot c_p \cdot T_3 \cdot \left(1 - \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}}\right) \quad (5)$$

And outlet conditions are:

$$h_3 = c_p \cdot T_3 \quad T_{4s} = T_3 \cdot \left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$$h_4 = h_3 - \frac{\dot{W}_T}{\dot{m}_T} \quad T_4 = \frac{h_4}{c_p} \quad (6)$$

- Combustor: first assumption in the combustor consists in neglecting the fuel mass when compared with the air mass flow:

$$\dot{m}_T = \dot{m}_C + \dot{m}_f \approx \dot{m}_C \quad (7)$$

Furthermore, a simplified energy balance has been also used:

$$\dot{m}_f \cdot H_p = \dot{m}_C \cdot c_p \cdot (T_3 - T_2) \quad (8)$$

Finally, according to the hypothesis:

$$p_2 = p_3 \quad (9)$$

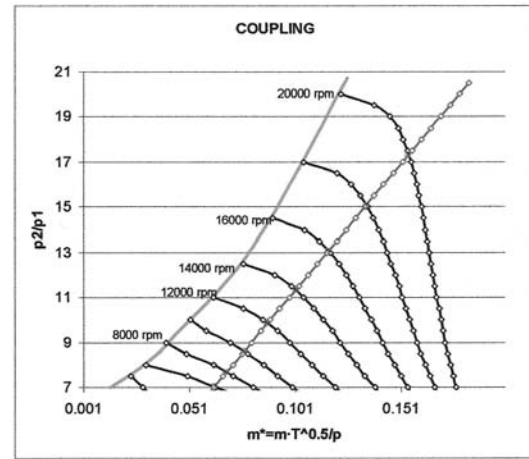


Fig. 3. Representation of the turbine characteristic line on the compressor flowchart. Intersections with constant speed lines determine the operating conditions.

- Shaft: a single shaft gas turbine engine is considered. Then the same speed is considered for both turbine and compressor:

$$n = n_C = n_T \quad (10)$$

Given that there are no mechanical losses (beyond those considered in the compressor and turbine efficiencies), engine power can be written as the result of a power balance:

$$\dot{W}_e = \dot{W}_T - \dot{W}_C \quad (11)$$

engine efficiency is then:

$$\eta_e = \frac{\dot{W}_e}{\dot{m}_f \cdot H_p} \quad (12)$$

Resolution method

The method is based on assuming a constant T_3 . This allows plotting the turbine characteristic flow line on the compressor flowchart. For that, considering (7), (9), (3) and the equivalence between p_1 and p_4 , the following transformation is performed:

$$\dot{m}_C^* = \dot{m}_C \cdot \frac{\sqrt{T_1/T_{1,0}}}{p_1/p_{1,0}} = \dot{m}_T \cdot \frac{\sqrt{T_1/T_{1,0}}}{p_1/p_{1,0}}$$

$$= A_{ef} \cdot \frac{p_2}{\sqrt{R \cdot T_3}} \cdot \phi \left(\frac{p_1}{p_2}\right) \cdot \frac{\sqrt{T_1/T_{1,0}}}{p_1/p_{1,0}} \quad (13)$$

From the intersection of this line with the constant speed lines of the compressor, it is possible to obtain the operation point for each speed. Graphical resolution is shown in Fig. 3.

Hence, the problem becomes completely determined: compressor outlet conditions and power can be calculated straightforwardly; the same with turbine outlet conditions and power. Finally, the energy balance at the combustor gives the fuel mass flow, and permits evaluating engine efficiency.

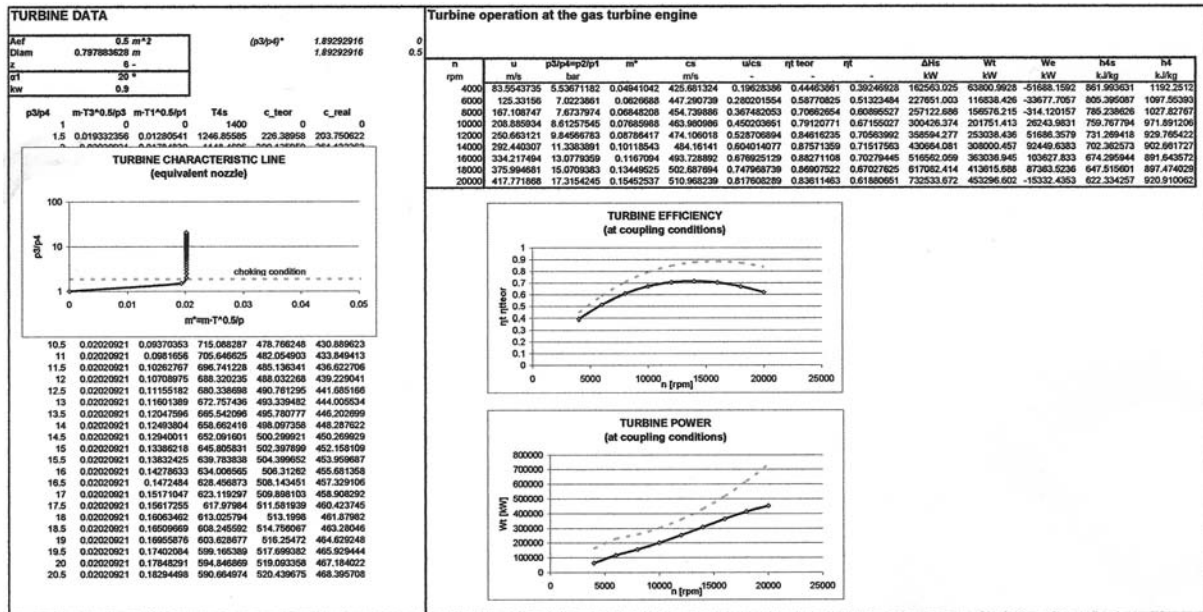


Fig. 4. General aspect of the ‘turbine’ sheet.

THE EXCEL SPREADSHEET

Calculation of the whole gas turbine is implemented in an Excel worksheet, using a set of interpolation functions known as Xlxfun [15]. The calculation is divided into four different aspects, and each aspect is included in a separate sheet. There is a sheet devoted to the compressor related data and calculations; another covers the turbine data and calculations; a third sheet calculates cycle overall values. Finally, a main sheet serves as user interface and summarizes the main results.

‘Turbine’ sheet

In this sheet, the different turbine parameters are specified, namely the effective area, A_{eff} , the number of stages, z , the angle at the stator blade outlet, α_1 , and the velocity coefficient, k_w . A general view of the turbine sheet is shown in Fig. 4.

The turbine operating curve is obtained as it is calculated in a convergent nozzle with an exit area equal to the effective area of the turbine.

The table on the right part of the sheet shows the results for all relevant variables at different speeds of the engine turbomachinery.

‘Compressor’ sheet

In this sheet all the experimental data concerning the compressor are included. More precisely, the curves of compression ratio, π_c , vs. corrected mass flow, \dot{m}^* , for each rotor speed (see Fig. 2) and the evolution of the isentropic efficiency at each rotor speed for different corrected mass flows are given. These data are used to find the operating point for the turbine/compressor assembly and to obtain the corresponding compressor efficiency.

A general view of the compressor sheet is shown

in Figure 5. Once again, the table on the right part of the sheet shows the conditions at the compressor outlet and inlet, and also compressor efficiency and power for each engine speed.

‘Gas turbine’ sheet

In this sheet the main results concerning the Brayton cycle engine are presented. The turbine and compressor power and the net power of the gas turbine are presented as a function of their speed; these values are obtained from the two precedent sheets. In this graph the useful engine range for the gas turbine can be determined (the range where the net power is positive). The engine thermal efficiency is also plotted vs. the turbomachinery speed (see Figure 6), where the best points concerning efficiency can be determined. The fuel/air equivalence ratio is also given.

‘Results’ sheet

Finally, the ‘results’ sheet is used as the user graphical interface. Figure 7 shows this aspect. In this, the user can modify some main parameters (A_{ef} , ambient conditions, T_3 , etc.) and the main results are reported. The following plots are shown in this sheet:

- Coupling line (turbine characteristic line on the compressor flowchart, in which intersections at each speed of the assembly have been marked).
- The effect of the turbomachinery speed on powers (\dot{W}_C , \dot{W}_T and \dot{W}_e), efficiencies (η_C , η_T and η_e), compression ratio, air-to-fuel ratio, and fuel and air mass flow.
- The equivalent Brayton cycle for the selected engine speed. In this plot both the ideal and the actual gas evolution are represented.

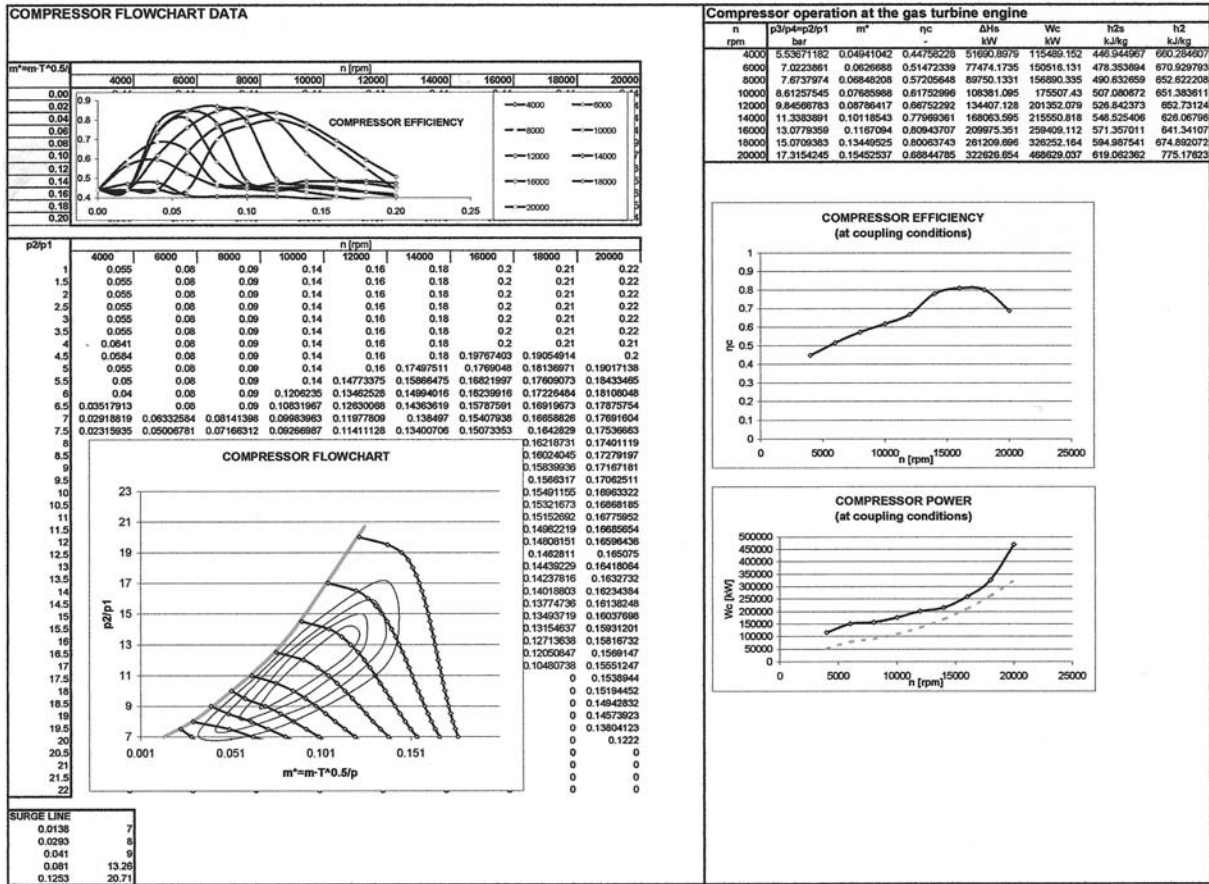


Fig. 5. General aspect of the 'compressor' sheet.

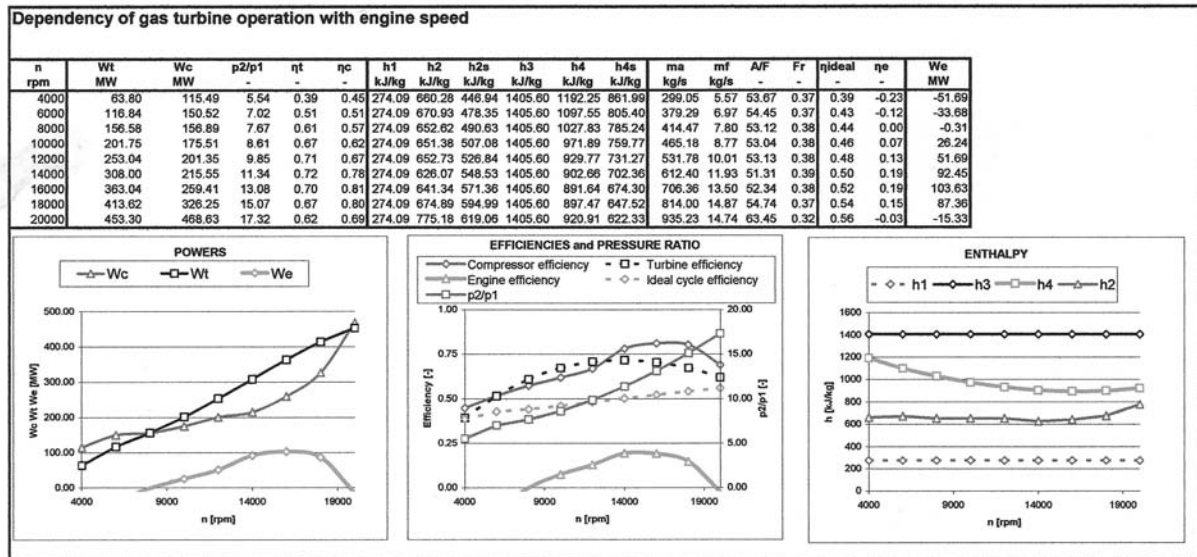


Fig. 6. General aspect of the 'gas turbine' sheet.

DISCUSSION

The potential of the presented methodology is interesting. As mentioned before, the computational tool allows the resolution of the problem of a compressor and a turbine coupling in quite a

realistic way. The problem is solved when a maximum T_3 is imposed, which is equivalent to full load in this type of engine; lower values of T_3 allow simulation of engine behavior at partial load. The main outputs that the student can display are the air and fuel mass flows, and thus the fuel/air

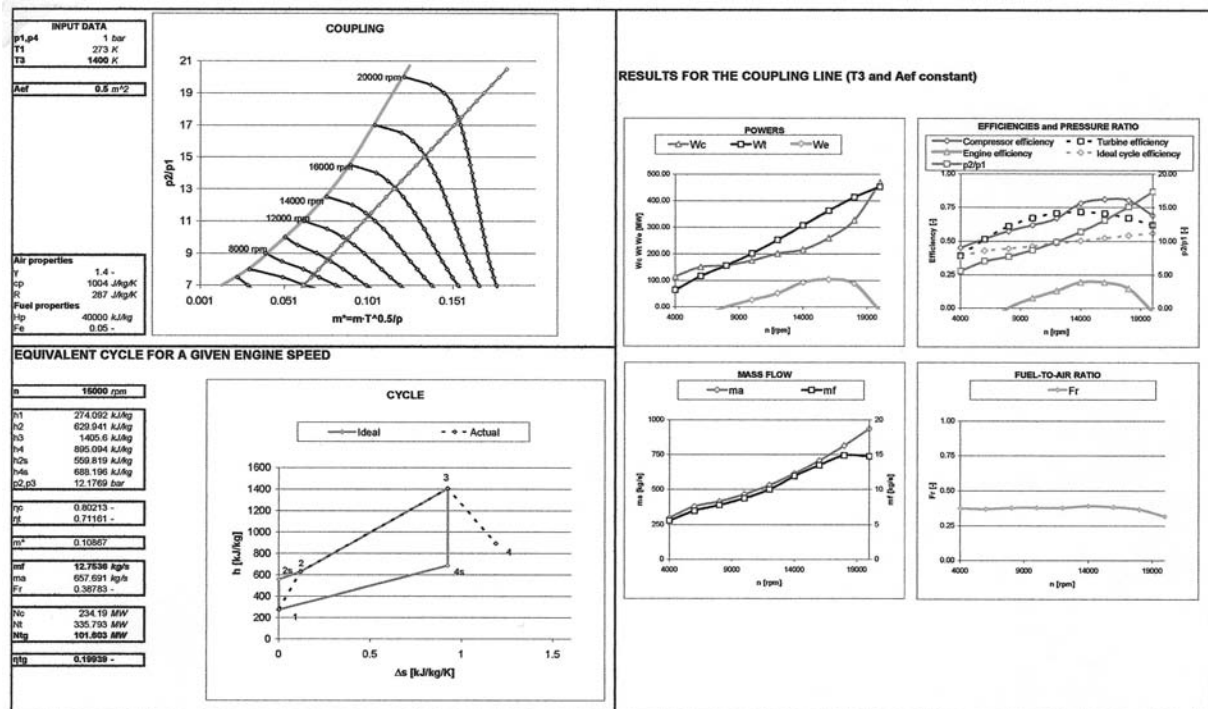


Fig. 7. General aspect of the 'results' sheet.

equivalence ratio, the net generated power and the thermal efficiency of the assembly. Obtained results are not far from reality and the effort to obtain them is very small. Hence, student effort is concentrated on understanding the basis of the problem, trying to discover the links between the different elements and parameters.

Beyond benefits in the improved comprehension of the gas turbine coupling problem, students gain the ability to use spreadsheets. From the authors' point of view, this has two benefits:

- 1) The spreadsheet approach used in the present work for solving the gas turbine coupling problem can be used in many other industry applications. The authors strongly believe that this kind of learning is very helpful for people that will be future engineers, since students should be able to solve (relatively) complex problems with the help of spreadsheets.
- 2) Another important benefit of this approach is that the students are using a standard software tool (Microsoft Excel) to solve a specific engineering problem.

CONCLUSION AND STUDENT'S REACTION

The Excel spreadsheet was used as a central part of a practical class. First application of the presented approach was in the 2005 fall quarter during the Combustion Engines course for third year students of Mechanical Engineering. 226

students, divided into nine classes (which yield to an average class of 25 students) worked with the presented Excel sheet during three hours. As the total number of computers in the class was 13, most students performed their work in two-student groups, which were freely set by the students.

Main conclusions of this experience are now summarized:

- Although students had worked previously with Excel, some of them had difficulties with it (even when not too much programming ability was needed). The problem was partially solved with the re-assignment of the two-person groups with the restriction that an habitual Excel user was always required.
- After a short explanation, students were able to check and analyze the effect of the temperature at the combustor outlet, and of the size of the turbine. Engine speed effect was also analyzed, and finally students drew the operating map of the gas turbine engine. Students included relevant graphs in a class report that was afterwards evaluated.
- Although all formulae were accessible, most students did not analyze them in depth: action of the teacher was required in order to focus students' attention on the spreadsheet cells containing the most relevant formulae, trying to link them with the theoretical review performed at the beginning of the practical work.

Students' feedback was obtained by means of a poll covering 1–5 rated evaluations on global aspects and on some specific aspects (organization, media availability, teacher quality, etc.). A mean

4.0 rate was obtained from a population of 72 results (which approximately correspond to 144 students, since the poll was non-mandatory). As a

comparison reference, the mean rank of the practical classes in the Thermal Engines area during the 2005 fall quarter was 3.9.

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