

# Guidance page for practical work 2: turbojets

## 1) Objectives of the practical work

The project objective is to study the operation of jet engines and show how they can be realistically modeled with ThermoOptim.

The practical work allows students to build models of jet engines of increasing complexity:

- Single flow at fixed point on the ground with a variant of a gas turbine equipped with a nozzle
- Single flow in flight with inlet diffuser
- Afterburner configuration and turbofan.

Students are thus led to consider the behavior of nozzles and diffusers, which are not part of the core components of ThermoOptim, but exist as external processes.

They are asked to make a first setting of the model parameters based on the values provided in the question, and then perform sensitivity studies by varying parameters such as compression ratio and turbine inlet temperature.

This relatively complicated practical work is designed for students who have studied gas turbines. If this is not the case, they should do it first.

This document is an excerpt from the guidance page with complete results, which is reserved for teachers. For this reason, the numbering of figures is flawed.

## 2) References

R. BIDARD, J. BONNIN, *Energétique et turbomachines*, Collection de la DER d'EDF, Eyrolles, Paris, 1979.

M. GIRAUD, J. SILET, *Turbines à gaz aéronautiques et terrestres*, Techniques de l'Ingénieur, Traité Mécanique et chaleur, B 4 410.

## 3) Main practical work

### 3.1 Question

A jet engine of the type that is commonly used in aviation is a simple modification of a gas turbine open cycle studied previously: the turbine is sized to only drive the compressor (figure 3.1). At the turbine outlet, the excess energy available in the gas at high pressure and temperature is converted into kinetic energy in a nozzle. The thrust results from the difference of momentum between intake and exhaust gases.

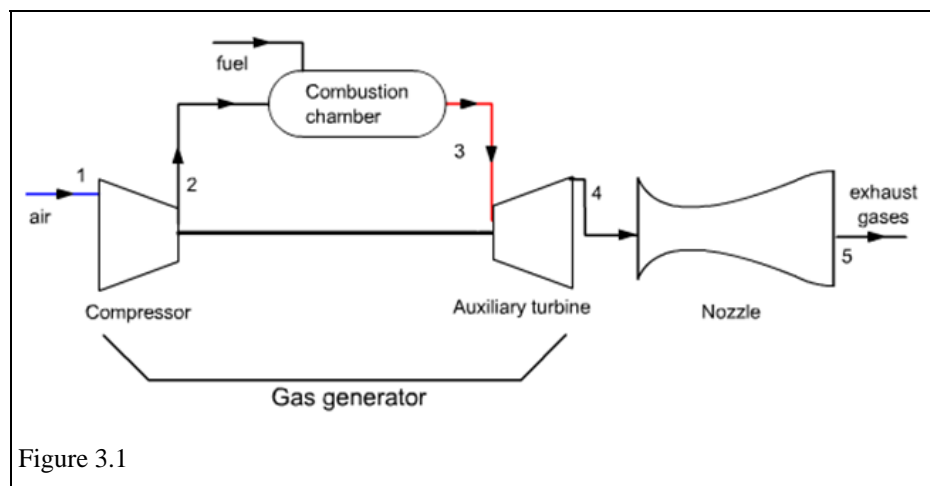


Figure 3.1

One of the characteristics of turbojet engines is that they operate in highly variable conditions of pressure and temperature: at sea level, take off and landing, the pressure is close to 1 bar and the temperature may reach 40 °C. In flight, pressure drops due to the altitude and reaches a few tenths of a bar, while the temperature drops below - 40 °C.

The objective of the work is to study such a cycle and to model it with ThermoOptim, using external components representing the nozzle and diffuser.

In the first part of the work, the aircraft will be assumed at the fixed point on the ground, and the engine to be a single-flow turbojet. The diffuser playing no role, students will be content to model the engine by adding a nozzle at the outlet of a simple gas turbine and balancing the power of the turbine with that of the compressor to find the nozzle inlet pressure.

In the second part they study the engine in flight, the dynamic pressure due to the speed of the aircraft being taken into account through an inlet diffuser.

In the third part, sensitivity studies performed on the model developed above will allow them to analyze the influence of key constructive parameters on the performance of the engine.

It is assumed in what follows that the compressor and turbine polytropic efficiencies are equal to 0.9, the turbine inlet temperature is equal to 1200 ° C and the air flow sucked is 65 kg/s, and that, in flight, the aircraft altitude is 10 km.

## 3.2 Models of the nozzle and diffuser

If it is legitimate to assume that the nozzle and the diffuser are adiabatic, it is however necessary to take into account the irreversibilities taking place in these organs.

Their thermodynamic study is at the intersection of fluid mechanics and thermodynamics of adiabatic flow. Two notes detailing the models corresponding to the external processes "nozzle" and "diffuser" are attached to these guidance pages.

These models are available in the ThermoOptim model library. Depending on circumstances, they may be handed directly to students, or they may be asked to propose their own models.

Two calculation methods are possible for the nozzle: to determine the output pressure knowing the output velocity, or to determine the output velocity knowing the output pressure.

Model parameters are:

- the gas inlet velocity (m/s);
- the isentropic efficiency of the process (0.95);
- either the gas output velocity (m/s), or the gas pressure at the exit of the nozzle, depending on the calculation option chosen.

Model input data are as follows (provided by the inlet component):

- the gas temperature  $T_a$  (°C or K) at the nozzle inlet;
- the gas pressure  $P_a$  (bar) at the nozzle inlet;
- the gas flow rate  $\dot{m}$  (kg/s).

The outputs are:

- either the gas pressure at the exit of the nozzle, or the gas outlet velocity (m/s), depending on the calculation

option chosen;

- the gas temperature at the nozzle exit.

Two calculation methods are possible for the diffuser: to determine the output pressure knowing the output velocity, or to determine the output velocity knowing the output pressure.

Model parameters are:

- the gas inlet velocity (m/s);
- the isentropic efficiency of the process (0.9) ;
- either the gas output velocity (m/s), or the gas pressure at the exit of the diffuser, depending on the calculation option chosen.

Model input data are as follows (provided by the inlet component):

- the gas temperature  $T_a$  (°C or K) at the diffuser inlet;
- the gas pressure  $P_a$  (bar) at the diffuser inlet;
- the gas flow rate  $\dot{m}$  (kg/s).

The outputs are:

- either the gas pressure at the exit of the diffuser, or the gas outlet velocity (m/s), depending on the calculation option chosen;
- the gas temperature at the diffuser exit.

### 3.3 Solving approach

For students to become familiar with aircraft engines, it is recommended that they begin by working on the Diapason session S20En\_aero<sup>1</sup>.

#### 3.3.1 Part 1

For students who have modeled a simple gas turbine cycle (if not, they must begin by working on the S20En and S24En sessions), the only difficulties concern the following:

- selection of component "nozzle"
- Balance of power of the turbine and compressor

The first difficulty is easily lifted by referring to the note Using external classes or by operating as shown in the first nine stages of the Diapason session S07En\_ext.

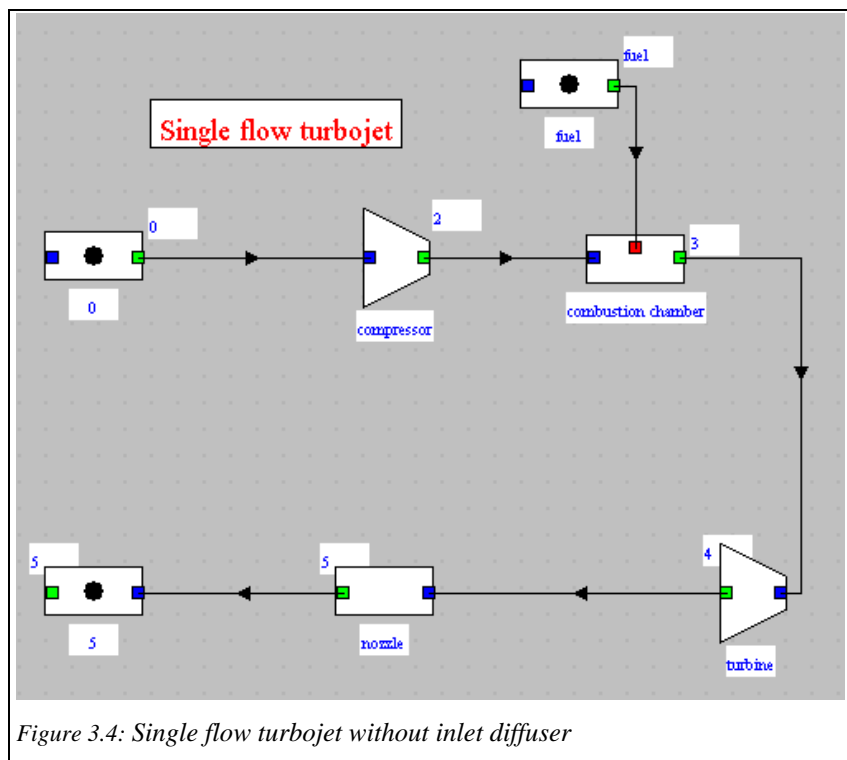


Figure 3.4: Single flow turbojet without inlet diffuser

<sup>1</sup> Séance S20\_aero : [http://www.thermoptim.org/SE/seances/S20\\_aero/seance.html](http://www.thermoptim.org/SE/seances/S20_aero/seance.html)

To solve the second, the procedure is as follows: as shown in Figure 3.5, bottom right corner of the turbine, an option allows you to choose to mechanically balance the turbine with another component of type "compression". Start by selecting this option, then double-click in the box just to the right. A screen lets you choose from among all the compression processes in the existing project (here there is only one, the compressor). Select the compressor. When computing, ThermoOptim automatically searches the turbine outlet pressure to balance the powers of the two components.

The expression of the thrust is,  $C_5$  being the velocity of exhaust gases:

$$F = - \dot{m}_5 C_5$$

The mass flow of fuel is:  $\dot{m}_c = \dot{m}_5 - \dot{m}_0$

### 3.3.2 Part 2

The second part deals with the study of the engine in flight, the dynamic pressure due to the speed of the aircraft being taken into account through an inlet diffuser. The diagram of the model is modified as shown in Figure 3.7.

The setting must be changed to reflect the flight conditions. We are assuming an aircraft speed of 224 m/s (Mach 0.75) and an altitude of 10 km.

For the pressure and temperature according to altitude  $z$ , we can use the table of the ICAO (International Civil Aviation Organization), attached hereto, or the approximate formulas below, the second being more accurate than the first,  $z$  being expressed in km:

$$T (^{\circ}\text{C}) = 12.65 - 3.67 z - 0.764 z^2 + 0.0653 z^3 - 0.00125 z^4$$

$$P (\text{mbar}) = 1006 - 113.8 z + 4.6 z^2 - 0.064 z^3$$

Choose a diffuser isentropic efficiency of 0.9.

Setting the rest of the model requires some precautions:

- Firstly, the compression ratio must be maintained, for this, the easiest way is to check "set compression ratio" and enter the previous value (20) in the corresponding field
- Then the screen of the nozzle must be updated, the external pressure being entering the "outlet pressure" field.

Once the model set, it becomes possible to calculate the engine performance. The specific thrust and consumption relative to the thrust are among the magnitudes most often used for this.

The expression of the thrust is here, taking into account the variation of the flow through the engine due to fuel injection:

$$F = \dot{m}_0 C_0 - \dot{m}_5 C_5$$

The mass flow of fuel is:

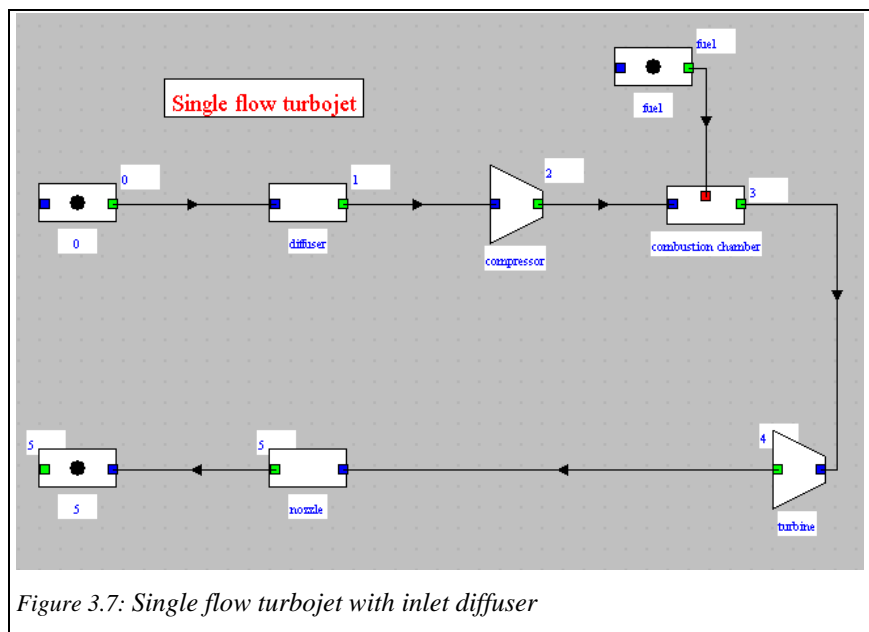


Figure 3.7: Single flow turbojet with inlet diffuser

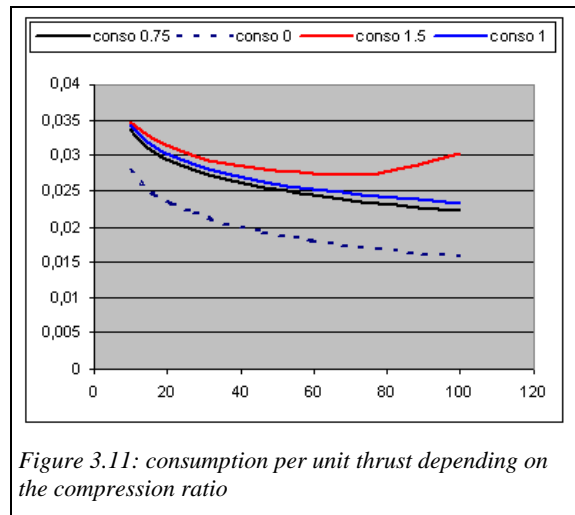
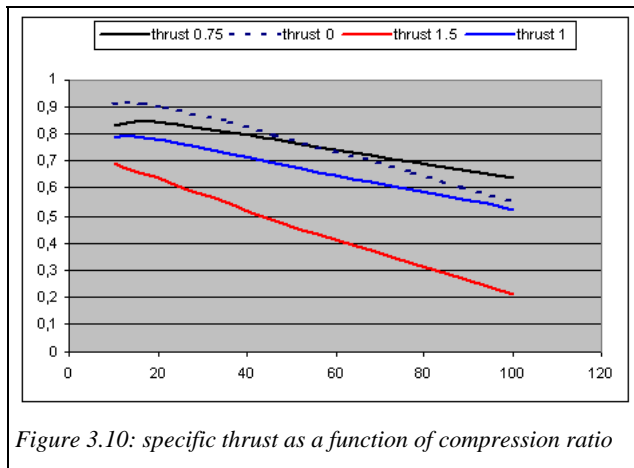
$$\dot{m}_c = \dot{m}_5 - \dot{m}_0$$

These quantities are often expressed in a reduced manner : thrust  $F$  is referred to the flow of intake air and fuel flow to the thrust, respectively, giving values of  $0.842 \text{ kN s kg}^{-1}$  and  $0.0294 \text{ kg kN}^{-1} \text{ s}^{-1}$ . They will be studied next section.

### 3.4 Sensitivity studies

Once the model is built and set, many sensitivity studies can be performed by the students.

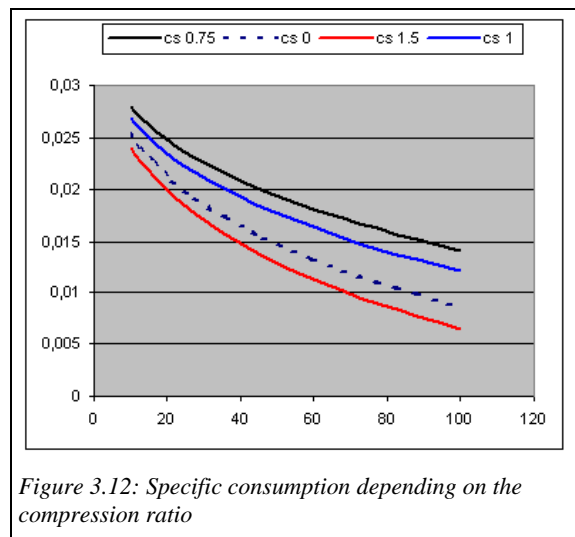
For example, if they are interested in the evolution of specific thrust or consumption per unit of thrust for various Mach numbers at given turbine inlet temperature they can achieve results such as those reproduced Figures 3.10 and 3.11.



The dotted curve for Mach = 0 corresponds to the performance on the ground at the fixed point, the others at different flight speeds in the same external conditions as before.

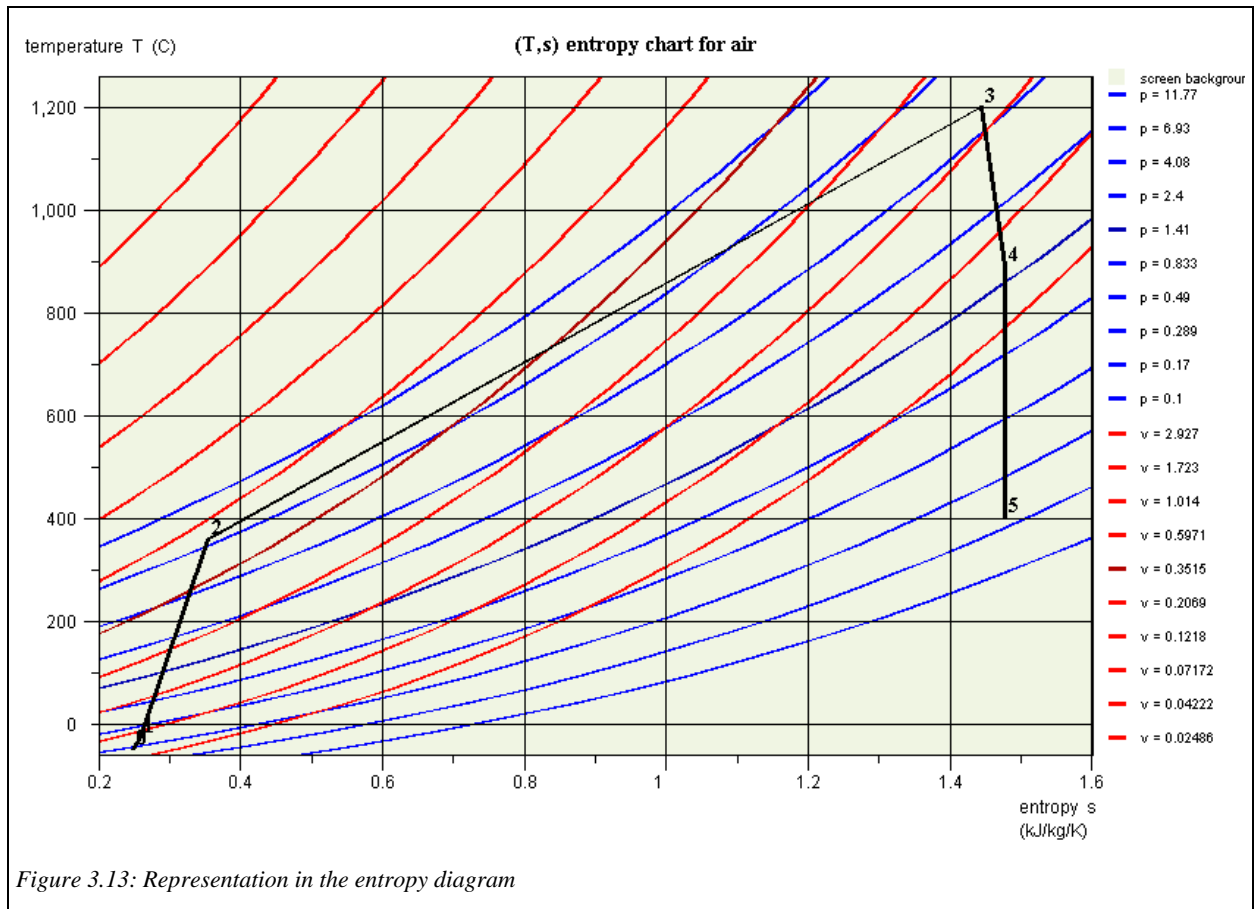
They show that the compression ratio that maximizes the thrust does not correspond to the minimum of consumption. So there is a trade-off, especially as the mass of the engine must also be taken into account, which gives priority to high specific thrust engines.

Figure 3.12 shows the specific consumption of the engine, product of the two quantities above. It is higher in altitude than on the ground for low speeds because the temperature is much lower whereas the turbine inlet temperature remains constant. However, when the aircraft speed increases, the dynamic pressure increases the temperature at the inlet of the combustion chamber and reduces the amount of fuel required. Ultimately, when it becomes sufficient, the ramjet engine can operate without a compressor or turbine.



Such sensitivity studies could also be used to study the influence of turbine inlet temperature on performance...

### 3.5 Plot in the thermodynamic charts



Une fois les points du cycle déterminés, il est possible de les représenter dans un diagramme thermodynamique. Once the points of the cycle determined, it is possible to plot it in a thermodynamic chart such as the entropy chart using the features offered by ThermoOptim. One difficulty is, however: the representation of this cycle on a thermodynamic chart is problematic because this is not the same fluid that runs through the entire machine. The change in composition in the combustion chamber prohibits in principle to plot the cycle in a single chart. In the air entropy chart, points 3, 4 and 5 do not appear on the right isobars, due to the change of working fluid.

Figure 3.13 shows the result. A comparison with a Carnot cycle can then be made.

### 3.6 Technological design

A possible activity if students have sufficient time is to ask them to calculate orders of magnitude of system sizing (sections of passage ...), to estimate the pressure drops in the combustion chamber, and refine the model accordingly.

#### 4) Variants

We propose a few variants, but many others can be imagined, depending on the time available, the level of the students, their number, and educational objectives pursued.

#### 4.1 Taking into account an afterburner in the model

It is possible to increase the thrust by raising the temperature of the gas at turbine outlet to give them a higher enthalpy, and thus a higher speed at the nozzle outlet. As to limit the inlet temperature in the turbine, the initial combustion takes place with high excess air, a large amount of oxygen is available. As the nozzle can also withstand high temperatures, it is possible to reach temperatures near 2000 K. We can thus obtain a significant additional thrust, but at the cost of an important additional fuel consumption.

## 4.2 Study of turbofans

From the previous model, it is possible to ask students to study turbofan engines and in particular to try and find the settings of their models to get the characteristics of an engine with high bypass ratio such as the CFM 56 General Electric engine designed for Airbus and a fighter low dilution engine such as the Snecma M88 which equips the Rafale. The fan is balanced by the LP turbine, the compressor by the HP turbine.

The only difficulty here concerns the creation and configuration of the divider splitting the incoming air flow between the compressor and the fan. To solve it, remember that the nodes do not propagate automatically point and substance names in the diagram. You must therefore take care to enter this information in the input tabs of processes located just downstream of the divider and the mixer. For a divisor as here, the point is naturally the same as that downstream of the main process.

Setting the flow distribution is done by entering 1 in the branch corresponding to the compressor, and the value of the dilution ratio in the one that leads to the fan.

The compression ratio in the fan is a parameter on which sensitivity studies can be made.

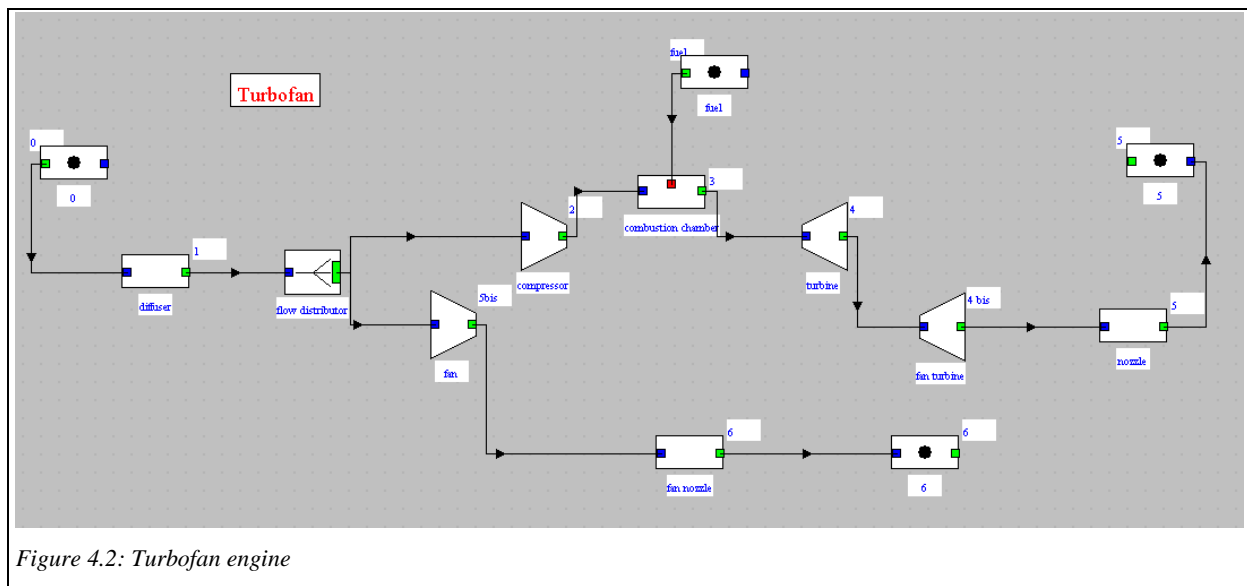


Figure 4.2: Turbofan engine

### 4.3 Study of turboprops

From the previous model, it is also possible to ask students to study turboprops of the type which equips helicopters, such as Turbomeca Arrius (Figure 4.3).

The fan is then replaced by the rotor blades.

### 4.4 Comparison with analytical model

Another possible activity is to ask students to develop an analytical model of the engine, assuming that the working fluid can be considered as perfect, the values of  $C_p$  and  $\gamma$  differing depending on the parts of the cycle, and to compare this model with that developed with Thermoptim.

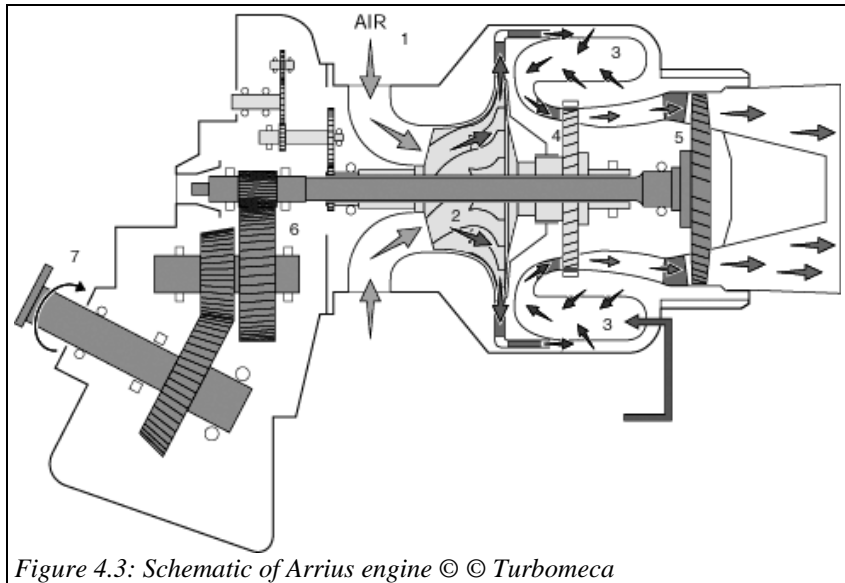


Figure 4.3: Schematic of Arrius engine © © Turbomeca

The results will be slightly different, but not much if the values of  $C_p$  and  $\gamma$  are well chosen.

The results will be slightly different, but not much if the values of  $C_p$  and  $\gamma$  are well chosen.

### 4.5 State of the art of turbojet technology

If the goal is for students to deepen their knowledge of turbojets, you can ask them to make a brief state of the art of technology used in these engines and the main constraints that exist at this level.

### 4.6 Cycle exergy balance

Finally, it is possible to ask students to build up the cycle exergy balance, if they have enough time.

Diapason session S06En<sup>2</sup> will provide necessary explanations on how to proceed.

### 4.7 Creation and use of a driver for sensitivity studies

If students have time and are interested in programming, the model we have developed is well suited to the creation of an external driver to guide calculations.

A driver can coordinate recalculation of a Thermoptim project under special rules. For our model, it allows to coordinate updates of the diffuser, the nozzle and the compression ratio in the whole project, calculate the quantities sought, even if they are not directly accessible, possibly save a file, and thus greatly facilitate sensitivity studies.

A driver is in the form of a special Thermoptim external class. This requires that students become familiar with the mechanism of external classes. Diapason session S07En\_ext<sup>3</sup> provides explanations on how to proceed.

<sup>2</sup> Session S06En : <http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/s06en-exergy-balances>

<sup>3</sup> Session S07En\_ext : [http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/s07en\\_ext-introduction](http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/s07en_ext-introduction)



The model is available in the Thermoptim model library. You can either ask the students to build such an external class, which requires an understanding of how Thermoptim performs its calculations, or simply content yourself to let them use this driver to perform sensitivity studies of the kind presented section 3.4.

Figure 4.5 shows a screen for the driver, with above the definition of the conditions outside the aircraft, in the middle a field to enter a value of the compression ratio to perform a single calculation, and in the bottom entry of compression ratio bounds to perform several calculations (10 in this case) and save the results.

The screenshot shows a software interface for a jet engine driver. It is organized into three main sections:

- Exterior conditions:** Contains three input fields: 'plane mach number' (0.75), 'ambient pressure (bar)' (0.265), and 'ambient temperature (K)' (222.15).
- Single compression ratio calculation:** Contains three input fields: 'compression ratio' (20), 'specific thrust' (0.842), and 'specific fuel consumption' (0.02943). A 'Calculate' button is positioned to the right of these fields.
- Various compression ratios simulation:** Contains two input fields: 'initial compression ratio' (10) and 'final compression ratio' (100). A 'Simulate' button is positioned to the right of these fields.

Below the interface, the caption reads: *Figure 4.5: Driver for the jet engine*

## 5) Work files, recommendations

### 5.1 Work files

The following work files are attached in the archive Turbojet.zip:

- programming note of external classes "diffuser", "nozzle" and of driver "thrust"
- extUser.zip file containing external classes
- Project and diagram files of the Thermoptim models presented here

### 5.2 Recommendations

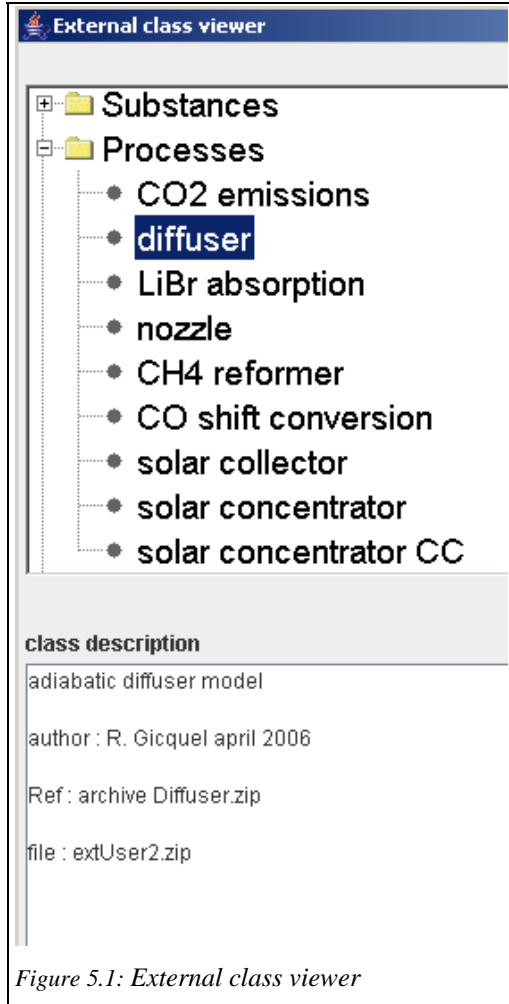
It is necessary that the teacher checks that students have at their disposal in their work environment Thermoptim external classes they need.

The easiest way to this is to run Thermoptim, then open the external class viewer (menu Special of the simulator). Classes will be grouped by type, class and "diffuser" and "nozzle" should appear respectively among the processes, as on figure 5.1.

If a class is missing, replace the extUser.zip file by that provided in the archive Turbojet.zip. If present, it is unnecessary to make this change

## Annex

Figure 5.2 provides a table of the ICAO (International Civil Aviation Organization), which gives P and T at altitude.



**External class viewer**

- Substances
- Processes
  - CO2 emissions
  - diffuser**
  - LiBr absorption
  - nozzle
  - CH4 reformer
  - CO shift conversion
  - solar collector
  - solar concentrator
  - solar concentrator CC

**class description**

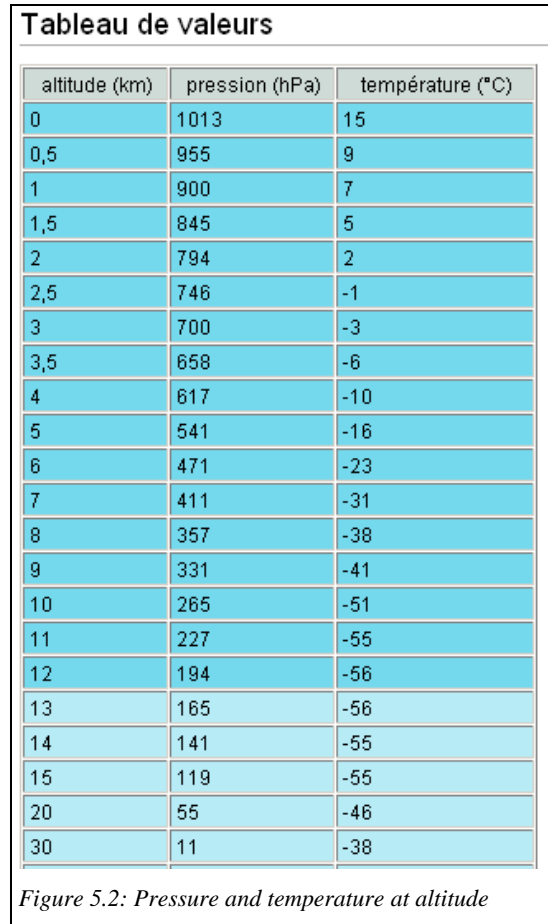
adiabatic diffuser model

author : R. Gicquel april 2006

Ref : archive Diffuser.zip

file : extUser2.zip

*Figure 5.1: External class viewer*



**Tableau de valeurs**

altitude (km)	pression (hPa)	température (°C)
0	1013	15
0,5	955	9
1	900	7
1,5	845	5
2	794	2
2,5	746	-1
3	700	-3
3,5	658	-6
4	617	-10
5	541	-16
6	471	-23
7	411	-31
8	357	-38
9	331	-41
10	265	-51
11	227	-55
12	194	-56
13	165	-56
14	141	-55
15	119	-55
20	55	-46
30	11	-38

*Figure 5.2: Pressure and temperature at altitude*