THERMOPTIM®

REFERENCE

MANUAL

VOLUME IV

EXTERNAL DRIVERS

TECHNOLOGICAL DESIGN

OFF-DESIGN CALCULATIONS

VERSION JAVA 1.7

CONTENTS

1 INTRODUCTION

In this Volume 4 we present a series of developments that have been made to allow completion of the Thermoptim core in order to address much more complex modeling than those presented in the other reference manuals, and in particular to :

- drive Thermoptim calculations taking control on the automatic recalculation engine;
- perform technological design and conduct studies of the behavior of systems operating off-design.

Given the extent of the area corresponding to these problems, we do not claim to provide them with comprehensive answers: we limit our ambition to provide a few relatively simple examples illustrating the potential of drivers and tools dedicated to technological design and off-design operation.

Advanced users willing to solve specific problems will have the task of building their own relevant models. Let us emphasize that this is an extremely interesting though very difficult topic, little addressed so far, probably because of lack of an appropriate tool, but essential if one wants to really understand how real machines behave. This document being a software reference manual, we will not develop thermodynamic analyses. We refer to Volume 3 of the Energy Systems[1] book the reader interested in further developments in this regard.

Until 2008, the the component models used in Thermoptim were rather simple: the phenomenological models built certainly allowed to study the thermodynamic cycle of the technology under consideration, but not to perform a specific technological design, or simulate performance in off-design operation, the latter two issues being much more complex than the first. To address these issues, we have been led to distinguish two levels in the models (their name was chosen to be as clear as possible, but it is not usual):

- phenomenological models, the only so far implemented in Thermoptim allow accurate calculation of thermodynamic cycles, regardless of the choice of a particular component technology;
- technological design and off-design operation simulation models not only provide the same results as the previous ones, but thanks to the inclusion of additional equations specific to the technologies chosen, allow more precise sizing of the various components and, once the technological design made, enable you to study the behavior of the system considered outside the operating conditions for which it was designed.

Such models are for example necessary when trying to assess the performance of an existing facility, which often operates under conditions different from those for which it was designed. These audit issues (especially focused at guiding improvements) intersest an increasing number of organizations, industrial or others.

The analysis of energy systems in off-design operation poses many problems much more difficult to resolve than those we encounter when we merely study the thermodynamic cycles in purely phenomenological terms, regardless technology choices.

Make clear that what we call off-design operation is steady-state operation of a facility for operating conditions other than those for which it has been designed: it is not the study of fast transients resulting for instance of control actuators.

In order to be able to design technological components it was necessary to refine the phenomenological models used in the Thermoptim core, by supplementing them appropriately.

As we shall see in this volume, the implementations of these new Thermoptim features are mostly made in the form of external classes, which provides flexibility for users to customize (see reference manual volume 3).

The classic phenomenological version Thermoptim remains unchanged: it is only complemented by a software layer able to take into account technological design and off-design operation models.

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[1] GICQUEL R., Systèmes Energétiques, Tome 3 : cycles et modélisations avancés, systèmes innovants à faible impact environnemental, Presses de l'Ecole des Mines de Paris, janvier 2009.

Technological design classes supplement the core allowing the consideration of the equations which are specific of the technological choices made, such as calculating the heat transfer coefficient U of a heat exchanger, or a compressor's volumetric and isentropic efficiencies.

Drivers ensure the systemic coordination of the various component calculations. They look for a set of coupled variables consistent with physical and technological problems posed, and allow to change the settings of a Thermoptim project.

Note that all the setting options available in the usual Thermoptim screens (phenomenological) are not necessarily valid in off-design operation, making it important to include in the external classes that are developed, tests to verify compliance with the assumptions of the models selected.

2 DRIVING THERMOPTIM

2.1 Overview

Driving Thermoptim has two main applications:

- firstly, facilitate the development of external classes by testing them gradually as they are defined;
- secondly provide access to all unprotected libraries for different uses (coordinate calculations of various components coupled together, make external treatments between recalculations, guide a user in a training module...).

To enable the external control, the main class of the simulator project can be subclassed, and a number of unprotected methods can be overloaded to define processings complementary to those of the core. Details of these methods are given in reference manual volume 3 annexes.

There are two ways to drive Thermoptim: either totally from an external application that instantiates the software and makes the settings, or partially, for a given project. An example relating to the first case is given in Volume 3. It is used to create the external classes and test them from the development environment external classes. It is presented in Section 6, which explains how to use a freeware software to dispose of a user-friendly development environment. We do not address this issue in this volume.

In the second case, on which we focus here, a specific driver class is assigned to a given project, and this class is instantiated when loading the project. It can then coordinate the recalculations of the project according to specific rules. The driver class is an extension of extThopt.ExtPilot, which derives from rg.thopt.PilotFrame. To associate it to the the project, an external class must be loaded into Thermoptim. Once the project is open, you must select the driver class that is associated with line "Driver frame" of the simulator Special menu (see Section 2.2.3). When the project is saved, the name of the driver class is saved so that it can be instantiated at a later loading. It is possible to save the driver data as well as those of external components, so that simulation results can be subsequently retrieved by the driver.

As discussed in connection with the examples included in this volume, this Thermoptim feature is extremely powerful because it allows you to customize the use of most elements of the software package, at the price of a quite reasonable programming work.

In this section, we present a driver that is used to calculate the energy balance of a solar Stirling engine. This is a very simple example which allows to introduce this type of external class without having to dwelve into the details of a complex thermodynamic model.

A Stirling engine is an engine of a particular type, working in closed systems, which implements a cooled compression and a heated expansion, so that the usual Thermoptim energy balance indicators cannot be directly used: the purchased energy is the sum of the heat supplied to the heat source (in this example a solar concentrator) and that provided to the heated expansion.

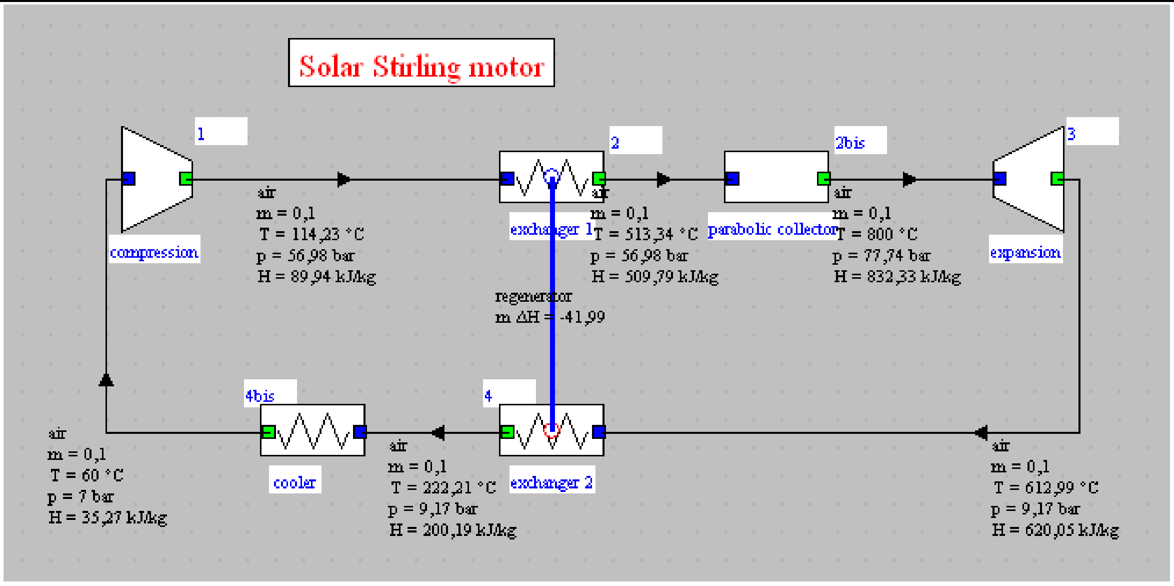
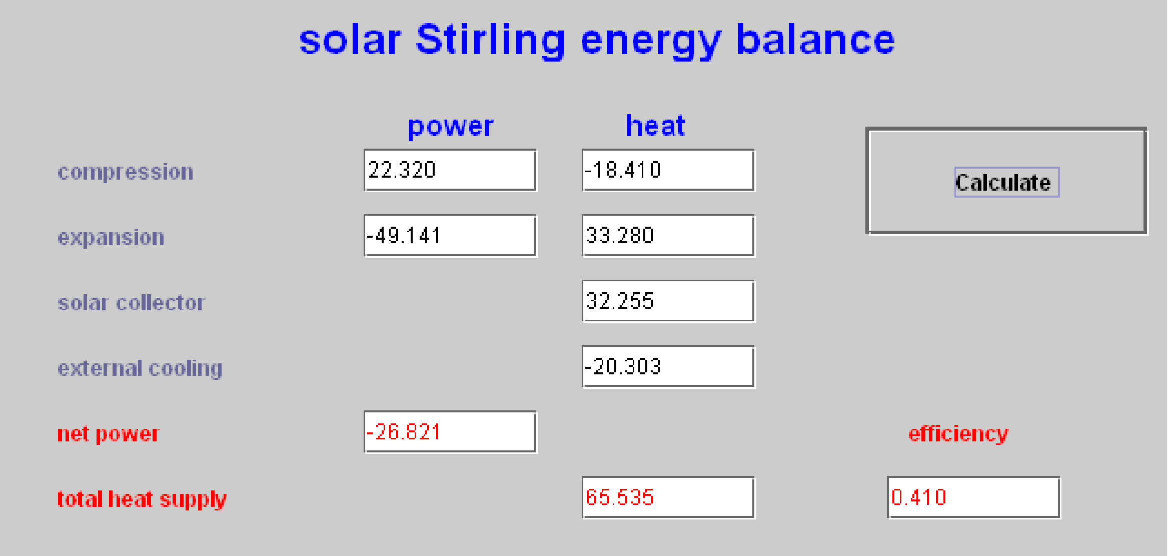


Figure 2.1 : Solar Stirling generator

The objective that we assign the driver is to provide a synthesis of the energies involved in the motor as heat or mechanical power, and calculate the cycle efficiency. Figure 2.2 shows the type of screen that you can imagine.



	power	heat	efficiency
compression	22.320	-18.410	
expansion	-49.141	33.280	
solar collector		32.255	
external cooling		-20.303	
net power	-26.821		
total heat supply		65.535	0.410

Figure 2.2 : Driver screen

2.2 Computer implementation

2.2.1 Creation of the class, visual interface

To create an external driver, simply subclass extThopt. ExtPilot. Achieving the visual interface poses no particular problem and we do not comment on here.

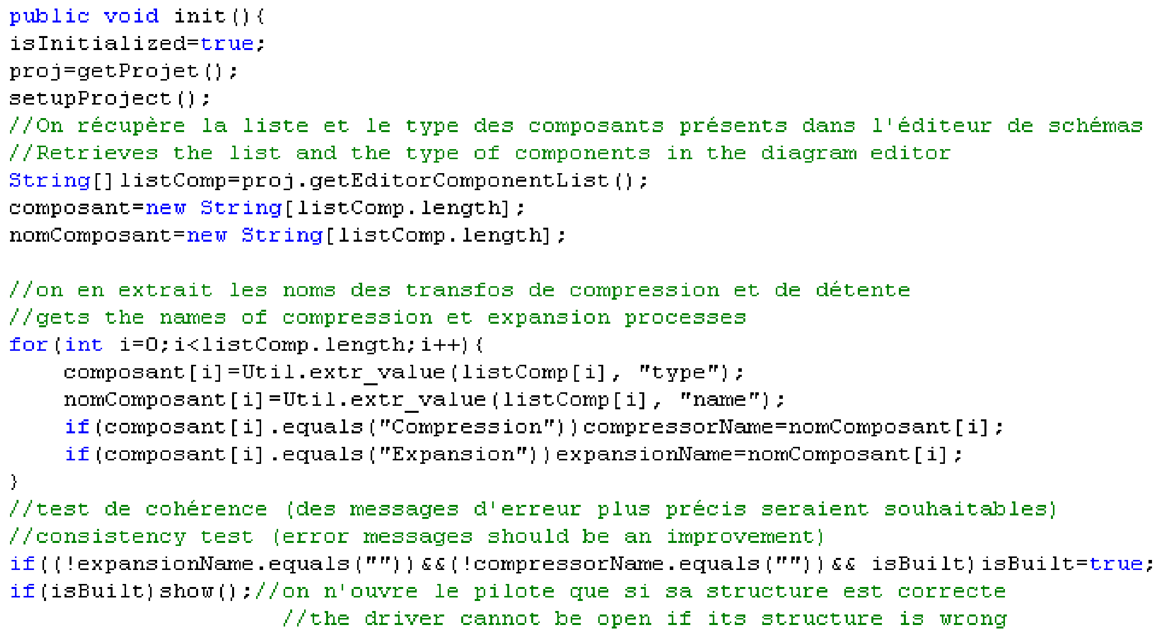
The constructor must end with a string specifying the code that will identify the driver in the list of those available:
type = "stirling";

It is also recommended to document the class:

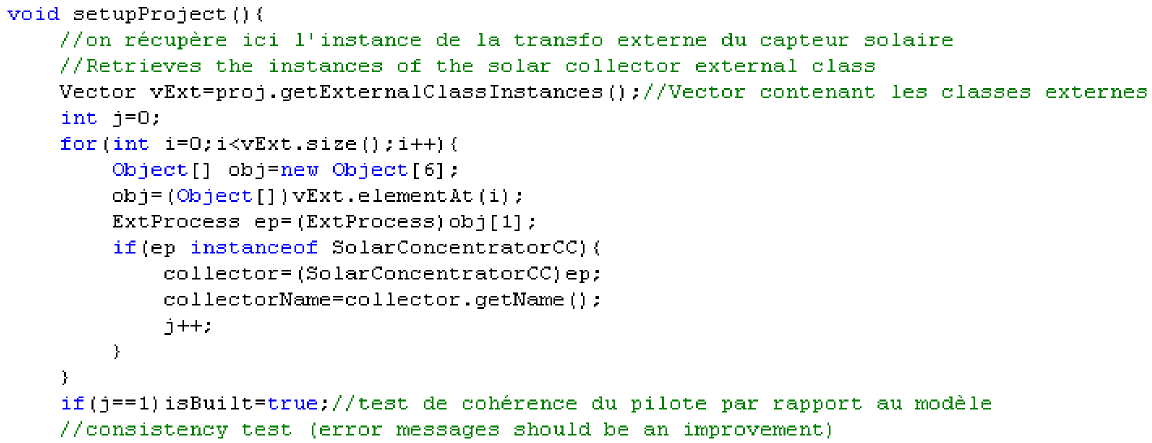
```
public String getClassDescription(){
   return "driver for a simple Stirling motor\n\nauthor : R. Gicquel february 2008";
}
```

2.2.2 Recognition of components names

It is possible to automatically recognize the names of the various components constituting the model, sorting them by type, which gives the driver greater genericity than if these names are entered as a String in the code. This is done by methods init () and setupProject (), which use methods to access the names of the components of the diagram editor and the list of external classes available (for the external process representing the concentration collector). Caution: if an appropriate diagram is not open in the editor, lists of components are empty and initializations cannot be done properly.



```
public void init(){
isInitialized=true;
proj=getProjet();
setupProject();
//On récupère la liste et le type des composants présents dans l'éditeur de schémas
//Retrieves the list and the type of components in the diagram editor
String[] listComp=proj.getEditorComponentList();
composant=new String[listComp.length];
nomComposant=new String[listComp.length];

//on en extrait les noms des transfos de compression et de détente
//gets the names of compression et expansion processes
for(int i=0;i<listComp.length;i++){
    composant[i]=Util.extr_value(listComp[i], "type");
    nomComposant[i]=Util.extr_value(listComp[i], "name");
    if(composant[i].equals("Compression"))compressorName=nomComposant[i];
    if(composant[i].equals("Expansion"))expansionName=nomComposant[i];
}
//test de cohérence (des messages d'erreur plus précis seraient souhaitables)
//consistency test (error messages should be an improvement)
if((!expansionName.equals(""))&&(!compressorName.equals("")) && isBuilt)isBuilt=true;
if(isBuilt)show();//on n'ouvre le pilote que si sa structure est correcte
                    //the driver cannot be open if its structure is wrong
```



```
void setupProject(){
    //on récupère ici l'instance de la transfo externe du capteur solaire
    //Retrieves the instances of the solar collector external class
    Vector vExt=proj.getExternalClassInstances();//Vector contenant les classes externes
    int j=0;
    for(int i=0;i<vExt.size();i++){
        Object[] obj=new Object[6];
        obj=(Object[])vExt.elementAt(i);
        ExtProcess ep=(ExtProcess)obj[1];
        if(ep instanceof SolarConcentratorCC){
            collector=(SolarConcentratorCC)ep;
            collectorName=collector.getName();
            j++;
        }
    }
    if(j==1)isBuilt=true;//test de cohérence du pilote par rapport au modèle
    //consistency test (error messages should be an improvement)
```

2.2.3 Calculations and display

Once the names of the various components are identified, we access their properties through the Project method getProperties(), which provides all the values you need.

As shown in the code, the execution of an external driver poses no particular problem. This one is particularly simple and simply calculates the energy balances for which the default Thermoptim calculating methods are inappropriate. It would be quite possible to complicate it slightly, so that it could update the simulator to perform the recalculations of the model before establishing the desired balance. We will present further examples involving such features.

```
void bCalculate_actionPerformed(java.awt.event.ActionEvent event){
    if(!isInitialized)init();//la première fois, on initialise, car il faut un constructeur sans argument
                             //pour instancier la classe par le RMI
                             //the initialization is made during the first call, as the constructor
                             //must have no argument because the class is instanciated by the RMI

    String[] args=new String[2];
    args[0]="process";
    args[1]=compressorName;//compression
    Vector vProp=proj.getProperties(args);
    String amont=(String)vProp.elementAt(1);//point amont //inlet point
    String aval=(String)vProp.elementAt(2);//point aval //outlet point
    Double f=(Double)vProp.elementAt(4);
    double deltaUcompr=f.doubleValue();//puissance compresseur //compression power
    f=(Double)vProp.elementAt(12);
    double Qcompr=f.doubleValue();//chaleur compresseur //compressor heat

    args[1]=expansionName;//détente //expansion
    vProp=proj.getProperties(args);
    amont=(String)vProp.elementAt(1);//point amont //inlet point
    aval=(String)vProp.elementAt(2);//point aval //outlet point
    f=(Double)vProp.elementAt(4);
    double deltaUexpan=f.doubleValue();//puissance détente //expansion power
    f=(Double)vProp.elementAt(12);
    double Qexpan=f.doubleValue();//chaleur détente //expansion heat

    args[1]=collectorName;//capteur solaire //solar collector
    vProp=proj.getProperties(args);
    f=(Double)vProp.elementAt(4);
    double solarHeat=f.doubleValue();//chaleur solaire //solar heat

    //calcul des performances globales du moteur et affichages
    //calculates the overall motor energies and displays them on the driver screen
    tauExpan_value.setText(Util.aff_d(deltaUexpan, 3));
    netPower_value.setText(Util.aff_d(deltaUexpan+deltaUcompr, 3));
    tauCompr_value.setText(Util.aff_d(deltaUcompr, 3));
    Q_value.setText(Util.aff_d(Qexpan+solarHeat, 3));
    eta_value.setText(Util.aff_d((-deltaUexpan-deltaUcompr)/(Qexpan+solarHeat), 3));
    expanHeat_value.setText(Util.aff_d(Qexpan, 3));
    comprHeat_value.setText(Util.aff_d(Qcompr, 3));
    solarHeat_value.setText(Util.aff_d(solarHeat, 3));
    extCooling_value.setText(Util.aff_d(-(Qexpan+solarHeat+deltaUexpan+deltaUcompr+Qcompr), 3));
```

2.2.3 Loading a driver

Loading a driver is done by selecting line "Driver frame" of simulator menu "Special". A combo then presents a list of available drivers (Figure 2.3). Select the one you want to load (here "stirling"), then validate.

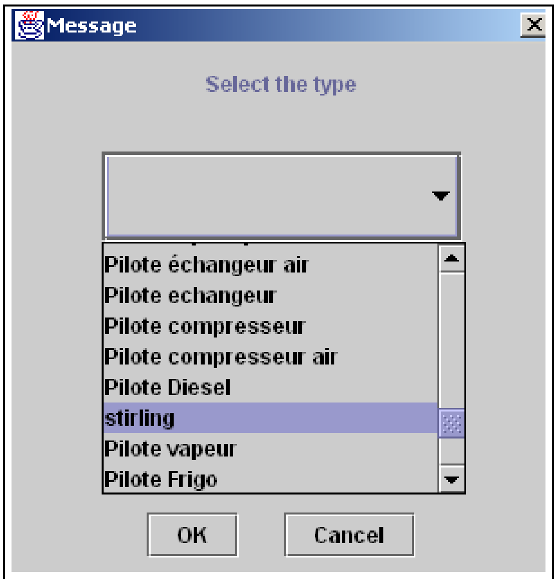


Figure 2.3 : Selection of the driver

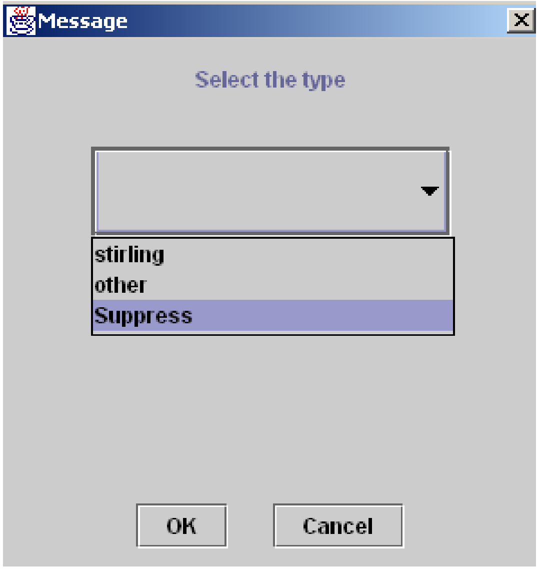


Figure 2.4 : Suppression of a driver

When a driver is already loaded, line "Driver frame" shows the screen of figure 2.4, which lets you either return to the driver loaded (line with its name), or select another, or delete the existing without replacing it. Only a single driver may be associated with a project.

3 TECHNOLOGICAL DESIGN

To perform technological design, we have introduced new screens, complementary to those that perform the phenomenological modeling. They can be activated by button "tech. design" placed in the usual screens of the different components.

These new screens allow you to define the geometric characteristics representative of the different technologies used and the parameters necessary to calculate them. For a given component, they obviously depend on the type of technology used.

In the next section, we present a summary of the principles adopted for modeling heat exchangers, compressors, turbines and expansion valves.

3.1 Component technological design

3.1.1 Heat exchangers

The most significant changes relate to heat exchangers, as earlier versions of Thermoptim only determine the UA value, which is the product of the overall heat exchange coefficient U by the exchanger surface A, the two terms not being evaluated separately. To resize a heat exchanger, that is to say calculate its surface, one must first choose a geometric configuration, and second compute U, which depends on that configuration, thermophysical properties of fluids, and operating conditions.

Recall that although the approach we have adopted in Thermoptim is unconventional, it has proved quite fruitful for the study of complex systems: a heat exchanger ensures the coupling between two "exchange" processes, one representing the hot fluid which is cooled, and the other the cold fluid which warms up. It follows that the definition of the exchanger flow patterns and geometry is made at the process level, and not globally.

3.1.1.1 Calculation

The method for calculating the heat exchanger in off-design operation is based on that the NTU method. When we know the two inlet temperatures and flow rates, an exchanger can be represented by a quadrupole, whose generalized matrix formulation can be expressed in various ways, depending on temperatures known (see chapter 5 of Volume 1 of Energy Systems book).

In design mode, the calculation of a heat exchanger is done in three steps:

- knowing the inlet and outlet temperatures and flows of both fluids, we first determine the efficiency ε, and we deduce UA by the NTU method
- then U is estimated by correlations depending on the exchanger flow pattern and geometry
- the calculation of area A is deduced immediately: $A = UA / U$

In off-design mode, if we know the inlet temperatures and flow rates of two fluids, the area A of the exchanger and its geometry (flow patterns and technological parameters), the calculation is done in three steps:

- determining U by correlations depending on the flow pattern and geometry of the exchanger ;
- calculating UA, product of U and A, and then NTU
- determining the effectiveness ε of the exchanger by the NTU method, and calculating the hot and cold fluid temperatures

Usually we know the inlet temperatures Tfe and Tce of both fluids and their flows mc and mf, and we wish to know the outlet temperatures Tcs and Tfs when known variables change. If we can determine the value of U, it is possible to calculate R and NTU, to deduce ε and determine Tcs and Tfs.

But other cases can also be solved: knowing Tfe, Tfs, mc, mf and U, we can calculate R, then NTU, deduce ε, and determine temperatures Tcs and Tce.

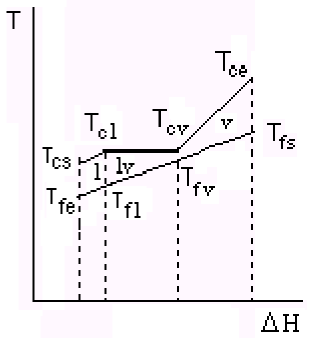


Figure 3.1 : multizone exchangers

The first case could already be calculated by the phenomenological version of Thermoptim: if at least two temperatures are set, the "off-design" calculation mode of the heat exchanger screen allows you to make the calculatation by the NTU method. As indicated in section of Volume 2 of the reference manual devoted to heat exchangers, this calculation applies to the study of an heat exchanger already designed for which one seeks to understand how it behaves in off-design conditions. Thermoptim updates the exchanger from the processs upstream links, then calculates the downstream temperatures. The points and processes associated are updated based on results.

It is therefore possible to use this calculation mode by changing the UA value as shown in the example discussed Section 4.

3.1.1.2 Multizone heat exchangers

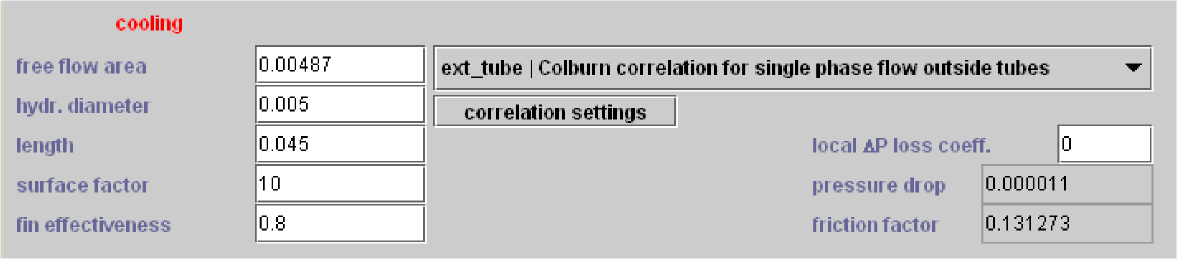
The calculation of multizone heat exchangers is more complex than simple ones, but it relies on the same principle. Let us consider the case of the condenser of a cooling machine whose temperature / enthalpy diagram is shown in Figure 3.1.

The refrigerant leaving the compressor is first desuperheated (T_{ce}-T_{cv}), then it is condensed at constant temperature, and then slightly subcooled (T_{cl}-T_{cs}). In this case, the calculation must be completed for each zone, the surface of the heat exchanger being the sum of the three zone areas. Obviously, the heat transfer coefficients are very different in these three areas.

In off-design mode, the total area remains constant, but its distribution among the three areas varies. A precise calculation is therefore requested to seek the solution that corresponds to the same total area and meets all other thermal and thermodynamic constraints.

3.1.1.3 Geometric setting

The geometric setting of heat exchangers is a difficult subject. Here we just introduce the quantities used, without discussing the reasons for their choice.



cooling

free flow area 0.00487

hydr. diameter 0.005

length 0.045

surface factor 10

fin effectiveness 0.8

ext_tube | Colburn correlation for single phase flow outside tubes

local ΔP loss coeff. 0

pressure drop 0.000011

friction factor 0.131273

Figure 3.2 : Condensor technological design screen

In order to calculate heat transfer coefficients and pressure drops, two geometrical quantities are particularly important besides the surface of the exchanger: the section Ac devoted to the fluid flow, and the hydraulic diameter dh. When the heat exchange coefficients of the fluids are very different, various devices such as fins can be used to compensate for the difference between their values. This is called extended surfaces, which can be characterized by an area factor f and a fin effectiveness η0.

These four parameters are those which have been chosen in Thermoptim to characterize heat transfer in each fluid. The length of the exchanger is also used for certain calculations such as pressure drops.

In the heat exchanger technological design screen, the following conventions are adopted:

- type configuration (here, "cond") is selected in a combo

- "free flow area" represents the flow area Ac
- "hydr. Diameter is the usual hydraulic diameter dh
- "length" is the length of the exchanger (used for calculating the boiling number Bo and the calculation of pressure losses, not yet implemented in the two-phase case)
- "surface factor" is the area factor f for large areas
- "fin effectiveness" is the fin effectiveness η0

3.1.1.4 Correlations for calculating the heat exchange coefficients

TABLEAU 12.1	TYPE	CORRELATION	TYPE DE FLUIDE
"int_tube"	inside tubes	Mac Adams	single-phase
"ext_tube"	outside tubes	Colburn (Dittus Boettler)	single-phase
"cond"	condensation int. tubes	Shah/Bivens	two-phase
"cond_ext_hor"	horiz. cond. ext. tubes	B1540 T/I	two-phase
"evap"	evaporation	Gungor Winterton	two-phase
"air_coil"	air coil	Morisot	air
"cool_tower"	evaporative cooling	Colburn	wet air
"flooded"	flooded	generic	two-phase
"plate"	plate	generic	single-phase

A major difficulty is the calculation of the overall exchange coefficient U, which depends on the fluid heat transfer coefficients h, by the general formula below. Many correlations have been proposed in the literature, and choosing the one best suited is not always obvious.

$$\frac{1}{U_c A_c} = \frac{1}{A_c \eta_{0,c} h_c} + \frac{e}{A\lambda} + \frac{1}{A_f \eta_{0,f} h_f}$$

The default options offered by Thermoptim are given in the table above. It summarizes the proposed configurations, indicating their type, the correlations used and the type of fluid to which they correspond. It is of course possible to introduce others in additional external classes.

Watch out: for the calculations to be meaningful, it is imperative that the Thermoptim project units are expressed in the SI system, that is to say that the flow is expressed in kg/s. Check out this item, preferably by introducing a specific test in the driver.

3.1.2 Compressors

3.1.2.1 Volumetric compressors

A volumetric compressor is geometrically defined by its swept volume, and its technological parameters allow to calculate its volumetric and isentropic efficiencies, according to its rotation speed, its load factor, and conditions of suction and discharge.

The models implemented in Thermoptim are based on the assumption that the behavior of volumetric compressors can be represented with reasonable accuracy by two parameters: the volumetric efficiency which characterizes the actual swept volume, and the classical isentropic efficiency ηs.

$$\lambda = a_0 - a_1 \frac{P_{ref}}{P_{asp}}$$

$$\eta_s = K_1 + K_2 \cdot \left(\frac{P_{ref}}{P_{asp}} - R_1 \right)^2 + \frac{K_3}{\frac{P_{ref}}{P_{asp}} - R_2}$$

The calculation of a compressor is made as follows:

- the isentropic and volumetric efficiencies are calculated from the equations above
- if we know the rotation speed, the swept volume and the volumetric efficiency, the volumetric flow can be calculated as: $\dot{V} = \frac{\lambda N V_s}{60}$
- knowing the suction density v, we deduce the mass flow: $\dot{m} = \frac{\dot{V}}{v} = \frac{\lambda N V_s}{60 v}$

In design mode, the rotation speed or the swept volume required to provide the desired flow is determined. The calculation is done taking into account the inlet and outlet pressures, and the flow value entered in the compressor flow field.

In off-design mode, the compression ratio determines λ and η_s, which sets the compressor flow and outlet temperature. The sequence of calculations is as follows:

- 1) knowing the inlet and outlet conditions, the compression ratio P_{ref}/P_{asp} and suction volume v are updated;
- 2) the volumetric and isentropic efficiencies λ and η_s and the actual flow are calculated knowing the rotation speed N;
- 3) the flow volume $\dot{V}$ is deduced;
- 4) the compressor sets $\dot{M} = v \dot{V}$ and spreads this value to connected components;
- 5) the useful work can then be calculated knowing the isentropic efficiency η_s.

3.1.2.2 Turbocompressors

Turbocompressors can be modeled in several ways. We will use a similitude approach by using two characteristics: the flow factor φ, and the enthalpy factor ψ, and we limit ourselves here to the simplifying assumption that their reduced characteristics (ψ, φ)and (η, φ)) can be represented by simple curves of parabolic type (Figure 3.3).

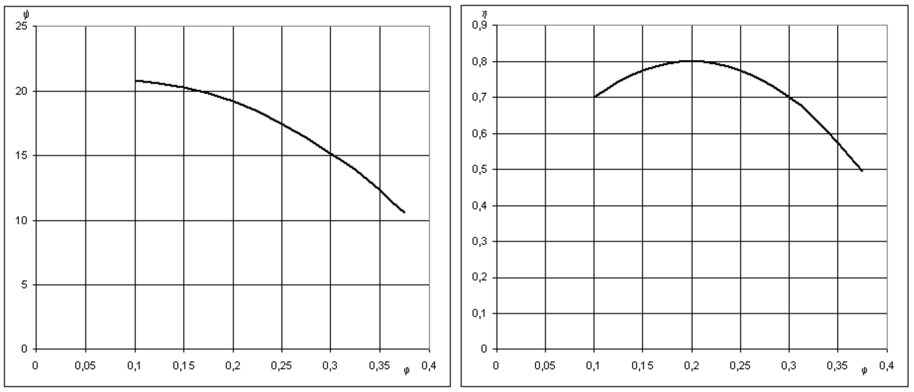


Figure 3.3 Simplified reduced characteristics of a turbocompressor

$$\varphi = \frac{(M_a)_c}{(M_a)_u} = \frac{240\ \dot{m}\ r\ T_a}{\pi^2 D^3 P_a N}$$

$$\psi = \frac{|\Delta h_s|}{1/2\ U^2} = \frac{7\ 200\ |\Delta h_s|}{\pi^2 D^2 N^2}$$

Other models are presented in the appendix.

3.1.3 Turbines

A turbine is geometrically defined by a section, and its technological parameters used to calculate the isentropic efficiency and the cone constant, depending on the conditions of suction and discharge.

For the isentropic efficiency, it is often possible to retain an equation analogous to the volumetric compressor law.

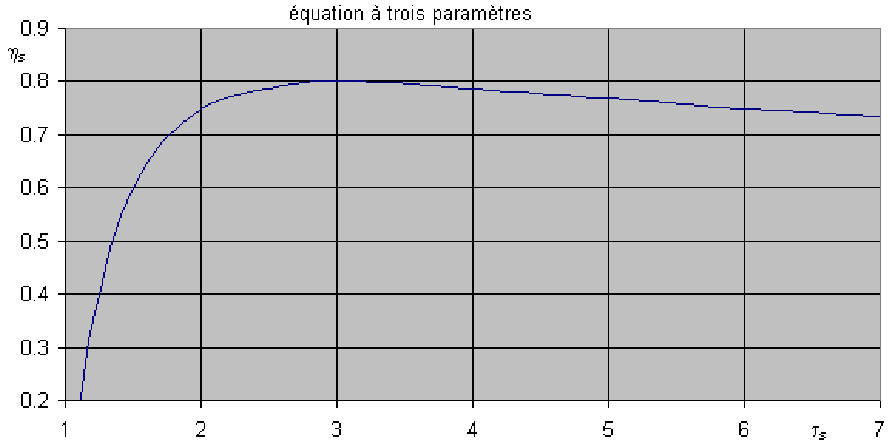


Figure 3.4 : Three parameter equation

$$\eta_p = \eta_{\lim} + (\eta_{\max} - \eta_{\lim}) \cdot \left(2 \left[\tau_{\max} \frac{P_{ref}}{P_{asp}} \right] - \left[\tau_{\max} \frac{P_{ref}}{P_{asp}} \right]^2 \right)$$

Note that it is expressed linearly as a function of expansion ratio and its square. Its parameters have the advantage of having a physical meaning.

$\eta_{\lim}$ is the asymptotic value of isentropic efficiency for the high expansion ratio, and $\eta_{\max}$ the maximum performance obtained for expansion ratio equal to $\tau_{\max}$.

The flow calculation is done using the Stodola rule, which can be expressed as follows, K0 being the cone constant:

$$\frac{\dot{m}\sqrt{T_{in}}}{P_{in}} = K_0 \sqrt{1 - \left[\frac{P_{out}}{P_{in}}\right]^{(k+1)/k}}$$

Usually, we take k = 1, which corresponds to a quadratic form. If the flow is shocked, this relation is simplified as $\frac{\dot{m}\sqrt{T_{in}}}{P_{in}} = \text{Cste.}$

Other models are presented in the appendix.

3.1.4 Expansion valves

The technological design of valves is taken into account in a simplified way, because we consider that their dynamics is much faster than that of other cycle components, and therefore they act as regulators.
The only parameter introduced at this level is the overheating value.

3.2 Computer Implementation

The structures of external classes allowing to address the technological design and off-design operation for the various components of Thermoptim's core have a number of similarities with those described in Volume 3, but also some differences that are explained by their characteristics. We will present them in due time.

As major developments have focused on compressors and heat exchangers, they shall be presented here.

3.2.1 General Principles

Firstly, we must ensure consistency with the "phenomenological" Thermoptim classes, which need to perform their calculations in the same way, technological screens being present or not.

This implies in particular that the technological screens should be separate from the "phenomenological" ones.

Then we decided to outsource as much as possible computer implementation so that users can customize the calculations as much as they want. Indeed, it is virtually impossible on the one hand to find completely generic formulations given the multiplicity of technological options, and on the other hand to develop algorithms robust enough to solve the corresponding sets of equations. By outsourcing these classes, users can relatively easily adapt them to the specific problems they face.

We therefore limited ourselves to make available a working infrastructure which should significantly facilitate their task.

In principle, we believe that calculations of technological design and off-design should be performed in external classes, so that those we have built into the core are essentially devoted to allow communication between it and external classes.

Indeed, the core objects being not directly accessible from the outside, the information exchange needs to be made following rules that are a little binding. We sought to make it as flexible and user-friendly as possible, further than was possible using communication methods presented in Volume 3. The methods we have implemented for this purpose are documented in the appendix.

3.2.2 Structure

In the component screens, button "tech. design" provides access to the technological setting screen. The technological setting screens can be managed centrally from the menu line "Technological design screens" of the "Technological Design" simulator menu.

The TechnoDesign class is the superclass of the technological setting screens. It is subclassed by screens specific to each component type, according to the principle presented Section 2.3 of Volume 3.

Method makeDesign() of TechnoDesign actually implements the technological design.

In TechnoDesign, classes derived from JPanel allow to change the settings according to the technological choices made.

External mother classes representative of the main types of components have been prepared. They are intended to be subclassed by users depending on their requirements.

The only way to instantiate the TechnoDesign recognized by the core is to do it in an external driver, then load them in Vector vTechno of this driver. Therefore, they become visible from the core and may be associated with their components. This choice means that the external drivers play a major role in the technological design and off-design operation.

Saving technological settings is done by the driver at the end of project files. The last line must end with a newline ("\ n"). Some TechnoDesign may require several lines (it is the case for heat exchangers, which use one for the overall results, and one for each fluid, as well as for thermocouplers who use two).

All technological design classes inherit from class extThopt.ExtTechnoDesign which has a JPanel called JPanel1, in which is designed the GUI.

It has two constructors :

```
public ExtTechnoDesign(Projet proj, String componentName, PointThopt amont, PointThopt aval){
}
```

```
public ExtTechnoDesign(Projet proj, String componentName){
}
```

The first assumes that the user defines his own upstream and downstream PointThopt, while the latter instantiates them automatically from the project properties, giving it greater genericity.

The PointThopt presented in appendix, which are kinds of external clones of the core points, give access to upstream and downstream states. The constructor instantiates a CorpsThopt (see Appendix) to help perform some thermodynamic calculations.

Method updateDeltaH() is used to update the enthalpy balance of the component. This class also has a method getFlow(), which allows to update the flow from the core.

We comment here two implementation examples, related to compressors and heat exchangers, which are used in the examples in this volume. Others are constructed similarly.

3.2.2.1 Volumetric compressors

The VolumCompr class includes:

- method setupPanel(), which builds the JPanel in the technological screen GUI, which is not detailed here. This interface allows to enter the necessary settings.
- generic methods for calculating the isentropic efficiency and flow, and display them on screen.

The constructors are:

```
public VolumCompr(Projet proj, String compressorName, PointThopt amont, PointThopt aval){
                super(proj, compressorName, amont, aval);
        this.compressorName=componentName;
        setupPanel();
}

public VolumCompr(Projet proj, String compressorName){
                super(proj, compressorName);
        this.compressorName=componentName;
        setupPanel();
}
```

They call for ExtTechnoDesign constructors, then, in order to use the specific name of compressorName, they identify it with componentName, and finally, they build the JPanel.

This class defines in particular the two methods for calculating isentropic and volumetric efficiencies:

```
  double getRisentr(){
        K1=Util.lit_d(K1_value.getText());
        K2=Util.lit_d(K2_value.getText());
        K3=Util.lit_d(K3_value.getText());
        R1=Util.lit_d(R1_value.getText());
        R2=Util.lit_d(R2_value.getText());

        double r_compr=aval.P/amont.P;
        double risentr=0.5;
        if(R1*R1+R2*R2==0)risentr=K1+K2/r_compr+K3/r_compr/r_compr;//3 parameter equation
        else risentr=K1+K2*(r_compr-R1)*(r_compr-R1)+K3/(r_compr-R2);
        risentr_value.setText(Util.aff_d(risentr,7));
        return risentr;
  }
```

```
   double getLambdaVol(){
            a0=Util.lit_d(a0_value.getText());
            alpha=Util.lit_d(alpha_value.getText());

            double r_compr=aval.P/amont.P;
            double lambda= a0-alpha*r_compr;
            display_value.setText(Util.aff_d(lambda,7));
            return lambda;
   }
```

Saving the parameter values is done using method saveCompParameters(), which, as we said above, should end with a line feed character.

```
   public String saveCompParameters(){
            String h="alpha_value="+alpha_value.getText()+tab
            +"K1_value="+K1_value.getText()+tab
            +"K2_value="+K2_value.getText()+tab
            +"K3_value="+K3_value.getText()+tab
            +"R1_value="+R1_value.getText()+tab
            +"R2_value="+R2_value.getText()+tab
            +"N_value="+N_value.getText()+tab
            +"Vs_value="+Vs_value.getText()+tab
            +"Device_number="+deviceNumber_value.getText()
            +"\n";//retour à la ligne impératif //compulsory line feed
     return h;
   }
```

3.2.2.2 Heat exchangers

A notable difference between a heat exchanger and a compressor is that the second is a single component, while the first is a thermal coupling between two exchange processes. However, the thermal coupling equations are the same for all types of heat exchangers that Thermoptim can calculate, with one exception: multizone exchangers often occur as exchange areas in which liquid and vapor two-phase boundaries are evolving over time. It is therefore impossible to assign to each a fixed area: they must be continually recalculated, even if the total area is known.

The heat exchanger TechnoDesign is called TechnoHx. In design mode, it calculates U and proposes a value of the exchanger surface A. It performs its calculations by estimating all thermophysical properties of fluids. Chapter 13 of volume 3 of the Energy Systems book specifies how they are determined.

The TechnoDesign for exchange processes is TechnoExch. It also allows to calculate the pressure drop when methods are implemented. To ensure a seamless calculation between the two processes and the heat exchanger it connects, TechnoHx makes a direct call to both TechnoExch associated, which are loaded on its screen. The process TechnoExch of an exchanger are thus not instantiated independently of theTechnoHx.

Different flow patterns have been introduced: they all inherit from FlowConfig and are selected in the TechnoExch screen. They make the calculation of thermophysical properties and the Nusselt number, especially for multi-zone heat exchangers.

In summary:
- TechnoHx introduces the exchanger surface, designs it (makeDesign ()), manages displays of calculations of thermophysical properties and instantiates cold and hot TechnoExch
- the cold and hot TechnoExch make the calculations of thermophysical properties and manage FlowConfig through a ComboBox. The JPanel for TechnoHexch appears in the TechnoHx window.
- FlowConfig implement the correlations for calculating the exchange coefficients and pressure drop
- the SettingsFrame of a FlowConfig allow to modify its settings.

The TechnoHx class constructor is as follows. It differs from the previous one because of the special structure of the class. It begins by retrieving the names of hot and cold processs that it matches, instantiates four PointThopt to get access to inlet and outlet states of both fluids, and builds their technological displays. He then tells each what is his counterpart. Finally, it configures the screen.

```
public TechnoHx(Projet proj, String hXname, PointThopt amontHot, PointThopt avalHot, PointThopt
amontCold, PointThopt avalCold){
                this();
                this.proj=proj;
                this.hXname=hXname;
    String[] args=new String[2];
    args[0]="heatEx";
    args[1]=hXname;
    Vector vProp=proj.getProperties(args);
    hotFluid=(String)vProp.elementAt(0);
    coldFluid=(String)vProp.elementAt(1);

    this.amontHot=amontHot;
    this.amontCold=amontCold;
    this.avalHot=avalHot;
    this.avalCold=avalCold;

    techc=new TechnoExch(proj, this, hotFluid, amontHot, avalHot);
    techf=new TechnoExch(proj, this, coldFluid, amontCold, avalCold);

    techc.setOtherTechnoExch();
    techf.setOtherTechnoExch();

        JLabCompName.setText(hXname);
          hotName.setText(hotFluid);
          coldName.setText(coldFluid);
          setupPanel();
    setupTechHx();
}
```

The class then implements a variety of methods to perform thermodynamic calculations.

The TechnoDesign constructor of "exchange" processes is similar to that of the compressor. There are actually three variants, their signatures differing because of the need for them to know whether they are connected to a heat exchanger (TechnoHx), a thermocoupler (TechnoT) or are isolated.

```
public TechnoExch(Projet proj, TechnoHx tHx, String exchangeName, PointThopt amont, PointThopt aval){
                this(proj, exchangeName, amont, aval);
                this.tHx=tHx;
}

public TechnoExch(Projet proj, String exchangeName, PointThopt amont, PointThopt aval){
                super(proj, exchangeName, amont, aval);
                this.exchangeName=componentName;
          setupPanel();
                JLabCompName.setText(exchangeName);
    fc=new IntTubeConfig(this);
    setupListeConf();
}
```

TechnoExch being the technological design class of exchange processes, it plays an essential role in the study of heat exchangers.

Global variables are defined as follows:

```
  boolean diph;
  TechnoHx tHx;
  TechnoExch otherTe;
```

```
   TechnoTC tTc;
   public FlowConfig fc;
   SettingsFrame sf;
   String[]listeConf;
```

diph allows one to specify that the calculation of exchange coefficients must be done in two phase mode.
tHx is the calling TechnoHx instance when TechnoExch is part of a heat exchanger.
otherTe is the second exchanger TechnoDesign in this case.
tTc is the calling TechnoTC instance when TechnoExch is part of a thermocoupler.
fc is the FlowConfig defining the flow pattern.
sf is the setting screen for the FlowConfig correlation coefficients
listeConf is a list of flow patterns available that allows the user to specify the type of flow pattern in which the fluid flows, and therefore the equations to be used to calculate the heat exchange coefficients.

Method setupListeConf() dynamically builds the FlowConfig list when loading Thermoptim, depending on external classes that define them. The codes defining these flow patterns and their description are loaded into a dropdown list so the user can make his choice. In case of doubt, if the list is too narrow, you can display the corresponding parameter by clicking on "correlation settings, which allows you to read the entire description (see Figure 3.11).

The constructor of the superclass is given below. It combines to the FlowConfig the TechnoExch who called on it, and initializes values needed to calculate the Nusselt number.

```
public FlowConfig (TechnoExch te){
       this.te=te;
       C1=0.023;a_Re=0.8;b_Pr=0.4;c_Visc=0.14;RR=0.001;
       te.JLabel13.setText("length");
       otherTe=te.otherTe;
}
```

To add another configuration, simply subclass FlowConfig and give it a reference that is not already used, then place the class in extThopt.zip or extUser.zip. It will automatically be included in listeConf.

Pressure drops are calculated in FlowConfig as follows.

In laminar flow, the losses are proportional to the flow rate and fluid viscosity: f = 64/Re.
For smooth tubes, f is given by the Blasius formula ($f = 0{,}316\ Re^{-0{,}25}$) if Re < 30 000, or by the following formula ($0{,}0032 + 0{,}221\ Re^{-0{,}237}$) for higher values of Re.

For rough pipes in turbulent regime (Re> 2100) the friction coefficient is given by the Colebrook equation:

$$\frac{1}{\sqrt{f}} = -\ 0{,}868589\ \ln\left[\frac{RR}{3{,}71} + \frac{2{,}51}{Re\sqrt{f}}\right]$$

$$RR = \frac{\varepsilon}{D}$$

ε = Absolute roughness of pipe

We can show that the implicit equation giving f can be approximated by:

$$\frac{1}{\sqrt{f}} = -\ 0{,}78173\ \ln\left[\left[\frac{RR}{3{,}71}\right]^{1{,}1} + \frac{6{,}9}{Re}\right]$$

The settings of SettingsFrame allow to calculate the pressure drop with the Colebrook formula if this option is selected, or with the Blasius one otherwise.

In two-phase system, pressure drop calculation of can be very complex, in particular because the different areas of the heat exchanger must first be determined.

In the vapor-liquid equilibrium zone, we use the approximate formula for the nuclear steam generator proposed by Herre and Gallori adjusted to take account of an nonzero quality inlet.

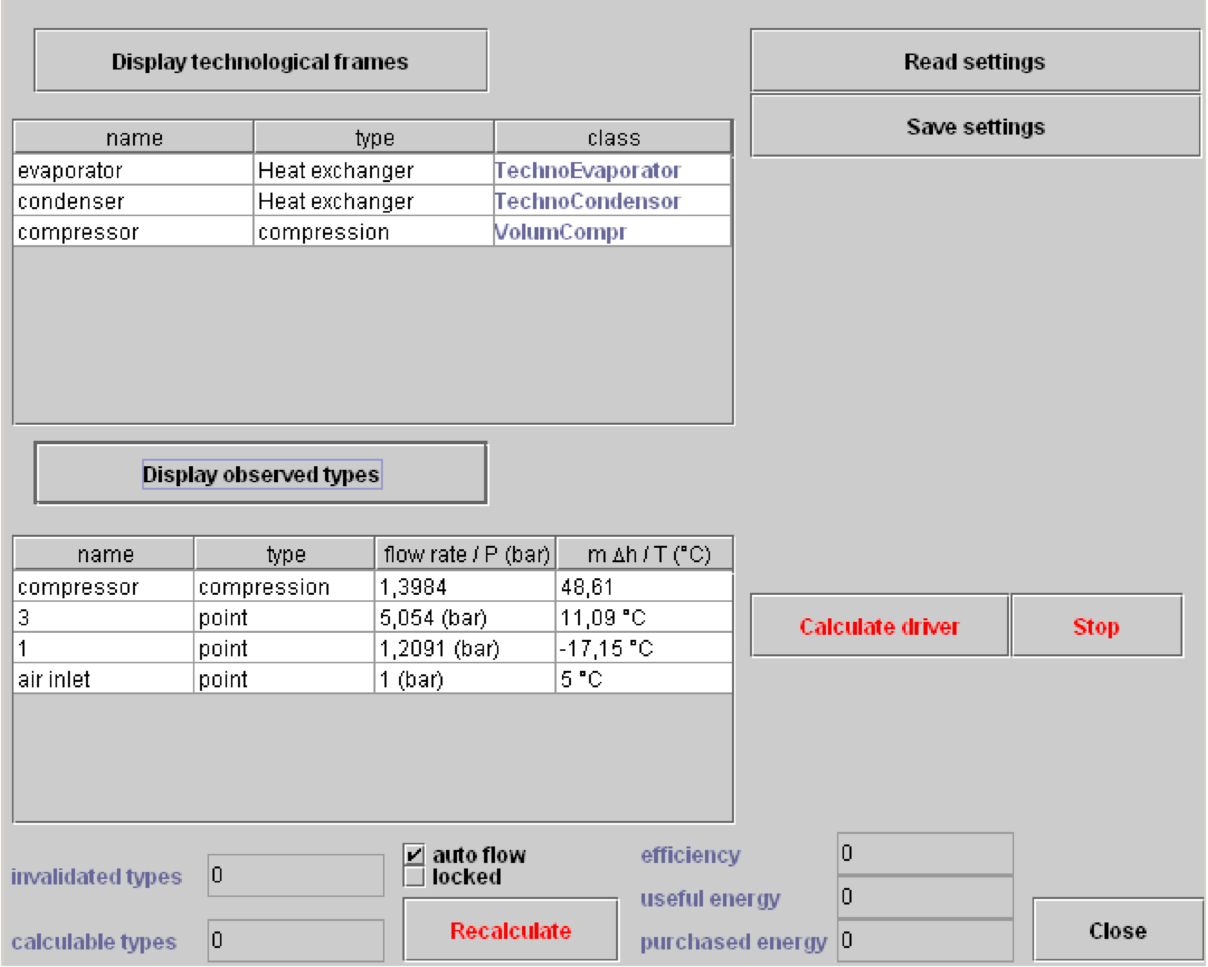
$$\Delta P_{diff} = \varphi\ \Delta P_{liq}$$

$$\varphi = \left[1 + |x_s - x_e| \left(\frac{\rho_l}{\rho_v} - 1\right)\right]\left[1 + |x_s - x_e| \left(\frac{\mu_l}{\mu_v} - 1\right)\right]^{-0,2}$$

The pressure drop is thus calculated from the saturated liquid state using this factor.

3.2.3 Technological and simulation screen

A technological and simulation screen has been added to the simulator. It is accessible from line "technological design screens" of the "Technological design" simulator menu (Figure 3.5), or by typing Ctrl T. It has two main tables placed in its left side. The upper one provides access to all TechnoDesign instantiated by the driver and loaded into Vector vTechno. Double-clicking on a line opens the TechnoDesign selected. The one below provides quick access to certain Thermoptim points or processes described as observed because we want to observe their thermodynamic state.



name	type	class
evaporator	Heat exchanger	TechnoEvaporator
condenser	Heat exchanger	TechnoCondensor
compressor	compression	VolumCompr

name	type	flow rate / P (bar)	m Δh / T (°C)
compressor	compression	1,3984	48,61
3	point	5,054 (bar)	11,09 °C
1	point	1,2091 (bar)	-17,15 °C
air inlet	point	1 (bar)	5 °C

invalidated types 0

calculable types 0

☑ auto flow

☐ locked

efficiency 0

useful energy 0

purchased energy 0

Figure 3.5 : Overall technological design tool screen

Buttons and displays at the bottom of the screen facilitate automatic recalculation, which can be triggered without returning to the simulator main screen.

The two buttons "Calculate the driver" and "Stop" can start and stop the calculations of the driver without blocking access to Thermoptim (it runs in a separate thread), which presents the advantage that it is possible to access all the software functions while it conducts operations coded in the driver. Button "Stop" can stop the calculations if necessary.

To use this feature requires that the calculation method of the driver be named calculatePilot(). Obviously, it is recommended not to make setting changes while the driver runs, to avoid interference.

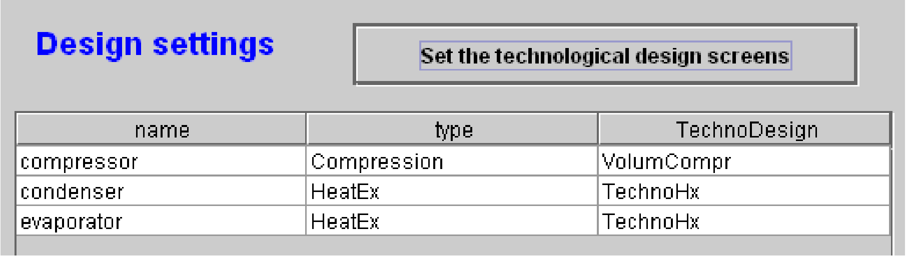
The two buttons at the top right, "Save Settings" and "Read Settings", allow you to save a technological setting made by a driver, and read it by a similar one, which avoids having to re-enter all the values each time you change driver.

3.2.4 Generic driver for creating technological screens

We show in Section 4 how to create screens by building technological drivers, which requires a minimum of programming. This work is imperative when you want to perform off-design calculations, because it is then necessary to take control of Thermoptim recalculation engine.

However, if you simply want to make the technological design of a project that only implements core Thermoptim components, it is possible to automatically create technological screens using the generic driver that we will briefly present. This avoids having to program one.

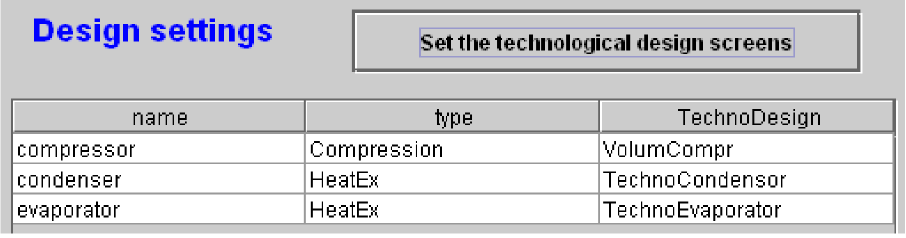
Open the Thermoptim project and load the generic driver by choosing the one whose title is "generic techno design pilot", in the list of drivers, then click "Set the technological design screens" (Figure 3.6). The list of components for which there are technological screens is displayed in the table with their name, type and technological screen class name instantiated by default: VolumCompr for the compressor and TechnoHx for the heat exchangers in Figure 3.6 example.



name	type	TechnoDesign
compressor	Compression	VolumCompr
condenser	HeatEx	TechnoHx
evaporator	HeatEx	TechnoHx

Figure 3.6 : Generic driver screen (default initialization)

In this example, this initial setting is suitable for the compressor, but not for heat exchangers: the condenser should be modeled by class TechnoCondensor, and the evaporator by TechnoEvaporator.

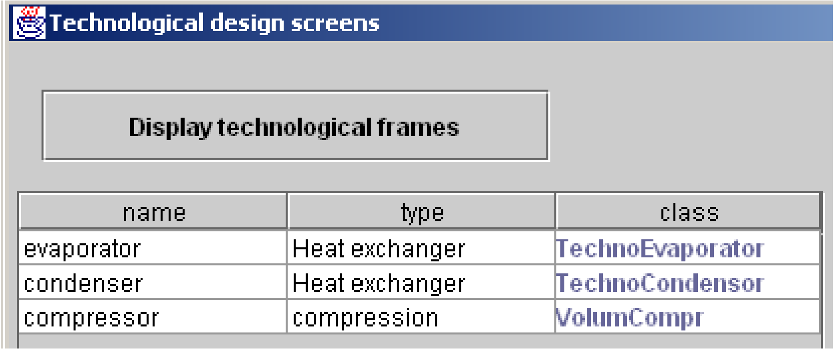


name	type	TechnoDesign
compressor	Compression	VolumCompr
condenser	HeatEx	TechnoCondensor
evaporator	HeatEx	TechnoEvaporator

Figure 3.7: Generic driver screen after selection

To change a component's TechnoDesign class, select its line and double-click. A message asks you to confirm your choice, then displays a list of available classes. Choose the one you want and confirm. After modifying the two heat exchanger classes, you get the screen shown in Figure 3.7.

You can then access the screens of these technological components either from their own screens (button tech. design") or from the technological and simulation window presented in the previous section. It can be opened from the simulator screen (Figure 3.8).



name	type	class
evaporator	Heat exchanger	TechnoEvaporator
condenser	Heat exchanger	TechnoCondensor
compressor	compression	VolumCompr

Figure 3.8 : Technological screen window

3.3 Example of heat exchanger design

3.3.1 Presentation and results

Consider a tube and fin heat exchanger intended to cool about 0.66 kg/min of air leaving a compressor at 5 bars and 275 °C with a flow rate of 1.17 kg/min of cold water passing through a coil of two parallel tubes. The diameter of the tube is 15 mm, and its thickness 1.5 mm. The spacing between the fins is 3 mm.

The exchanger can be easily modeled in Thermoptim.

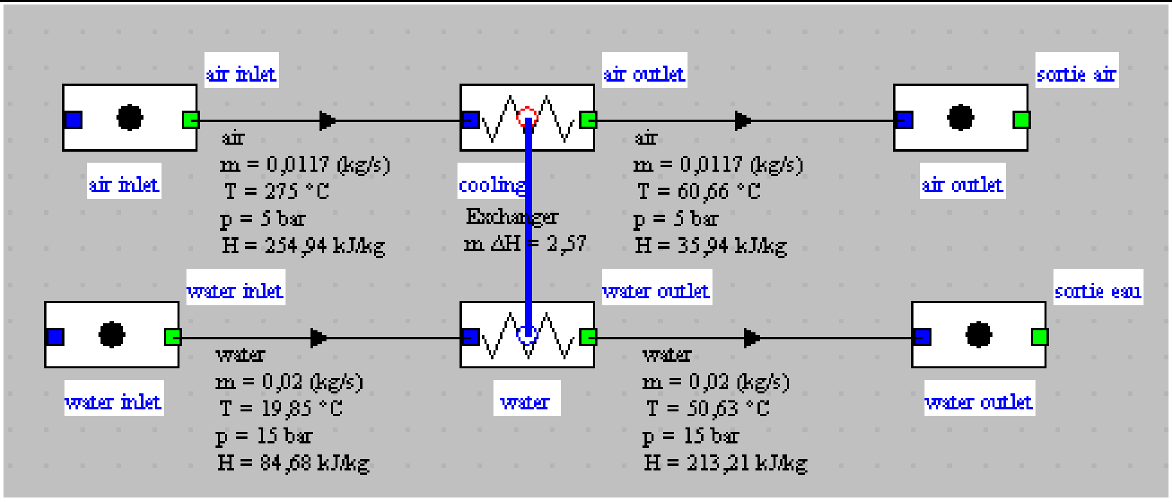


Figure 3.9 : Example synoptic diagram

To design the heat exchanger, we set an effectiveness of 0.84.

Using the Thermoptim technological design screens, it is possible to calculate the overall heat exchange coefficient and to deduce the area required to transmit the desired power.

This requires determining the hydraulic diameter dh and flow section Ac of both fluids.

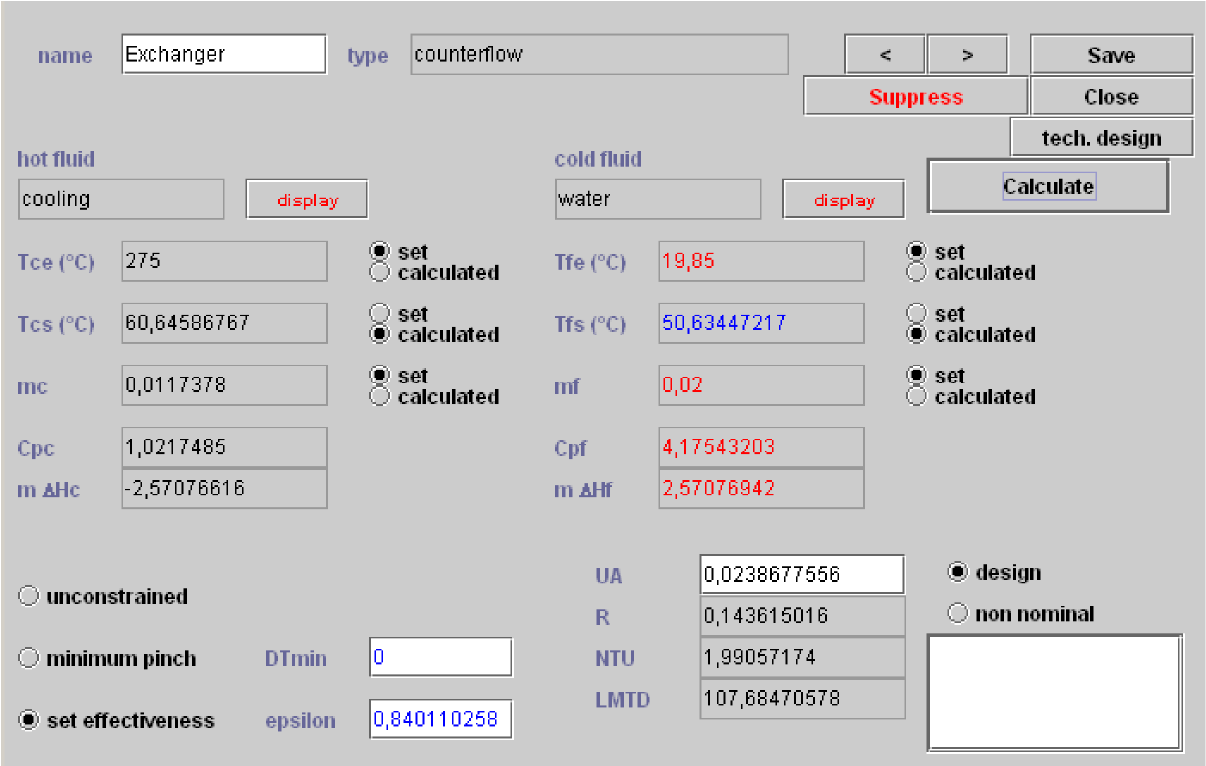
Inside the tubes, dh is given, and the calculation of Ac is very simple: it is equal to the product of the number of tubes by the tube section. Outside the tubes, the calculations are somewhat more complicated. dh is equal to 4 times the flow area by the wetted perimeter and Ac is the cross-sectional area available to the air.

We assumed that the fins multiplied the exchange surface by 4, their effectiveness being equal to 0.8.

These values must be entered in the heat exchanger technological design screen. After some trial and error, we obtain a setting similar to that of figure 3.11.

The driver can then calculate the area needed, which is here equal to 0.067 m^2, the exchange coefficients being 669.3 W/m^2/K on the air side, and 759.1 W/m^2/K on the water side, leading to a global coefficient equal to 355.7 W/m^2/K.

The heat exchanger will be comprised of two 90 cm tubes arranged in a 3 layer coil and traversing steel sheets separated from each other by 3 mm, with a total extended area of 0.31 m^2.



name Exchanger
type counterflow

hot fluid cooling
cold fluid water

Tce (°C) 275 ● set ○ calculated
Tcs (°C) 60,64586767 ○ set ● calculated
mc 0,0117378 ● set ○ calculated
Cpc 1,0217485
m ΔHc -2,57076616

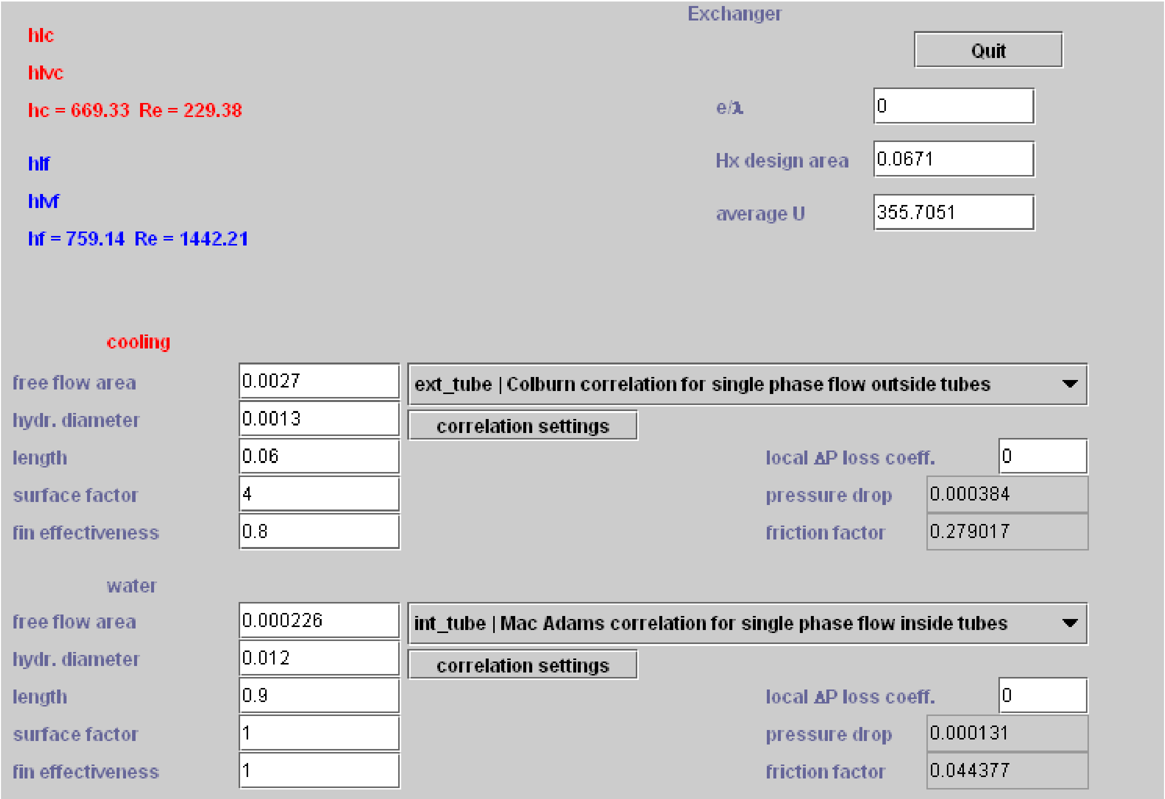
Tfe (°C) 19,85 ● set ○ calculated
Tfs (°C) 50,63447217 ○ set ● calculated
mf 0,02 ● set ○ calculated
Cpf 4,17543203
m ΔHf 2,57076942

○ unconstrained
○ minimum pinch DTmin 0
● set effectiveness epsilon 0,840110258

UA 0,0238677556
R 0,143615016
NTU 1,99057174
LMTD 107,68470578

● design
○ non nominal

Figure 3.10 : Heat exchanger screen



Exchanger

hlc
hlvc
hc = 669.33 Re = 229.38

hlf
hlvf
hf = 759.14 Re = 1442.21

e/λ 0
Hx design area 0.0671
average U 355.7051

cooling
free flow area 0.0027
hydr. diameter 0.0013
length 0.06
surface factor 4
fin effectiveness 0.8
ext_tube | Colburn correlation for single phase flow outside tubes
local ΔP loss coeff. 0
pressure drop 0.000384
friction factor 0.279017

water
free flow area 0.000226
hydr. diameter 0.012
length 0.9
surface factor 1
fin effectiveness 1
int_tube | Mac Adams correlation for single phase flow inside tubes
local ΔP loss coeff. 0
pressure drop 0.000131
friction factor 0.044377

Figure 3.11 : Technological design tool screen

As we said in the previous section, it is here possible to use the generic driver to build this technological screen. However, as this simple example lends itself well to a first driver presentation, we explain below how to create one.

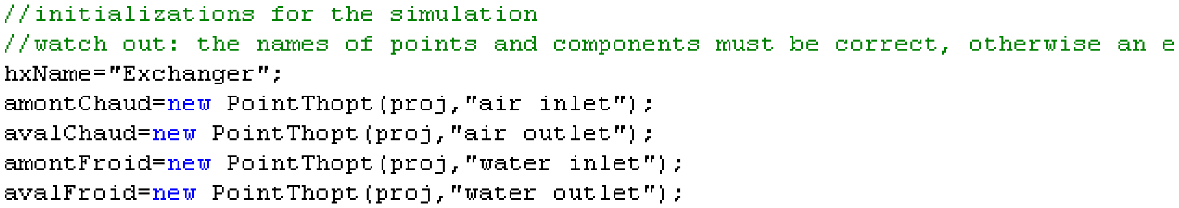
3.3.2 Driver implementation

The driver class is called AirExchangerDriver. Its interface is simple and classical, we do not break it here.

3.3.2.1 Initializations

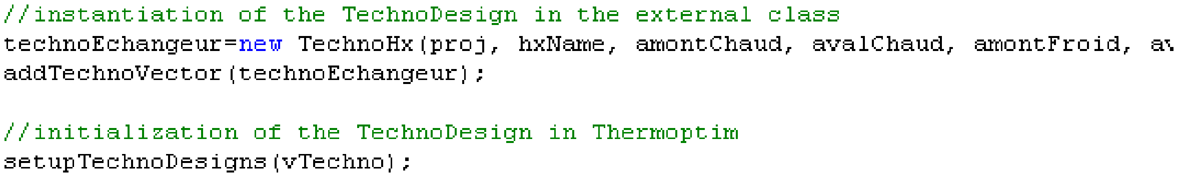
For the name of the exchanger, we could use the Project method getHxList(), but it requires the diagram to be loaded in the diagram editor. To avoid this constraint, it can be declared in the code.

For the other initializations we use PointThopt instances, which are kind of clones of Thermoptim core points giving easy access to their values. Four of these objects are instantiated, representing the inputs and outputs of the two fluids. Here we have their names entered by hand, but it would be possible to automatically recognize them.



```
//initializations for the simulation
//watch out: the names of points and components must be correct, otherwise an e
hxName="Exchanger";
amontChaud=new PointThopt(proj,"air inlet");
avalChaud=new PointThopt(proj,"air outlet");
amontFroid=new PointThopt(proj,"water inlet");
avalFroid=new PointThopt(proj,"water outlet");
```

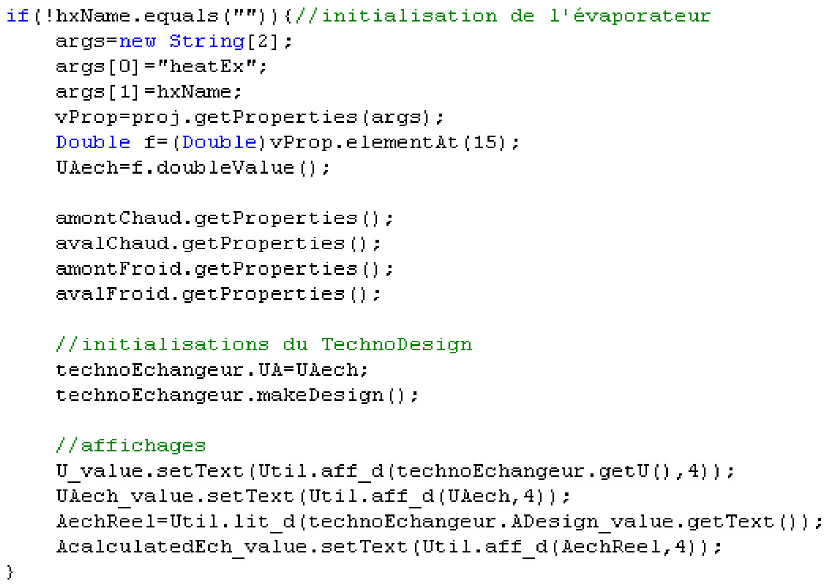
The screen technology is then instantiated and the Vector vTechno built :



```
//instantiation of the TechnoDesign in the external class
technoEchangeur=new TechnoHx(proj, hxName, amontChaud, avalChaud, amontFroid, av
addTechnoVector(technoEchangeur);

//initialization of the TechnoDesign in Thermoptim
setupTechnoDesigns(vTechno);
```

The last line initializes the TechnoDesign when opening an existing project file or loading the original driver. Without it, it does not appear in the TechnoDesign list of the technological and simulation screen of Figure 3.5.

3.3.2.2 Calculations



```
if(!hxName.equals("")){//initialisation de l'évaporateur
    args=new String[2];
    args[0]="heatEx";
    args[1]=hxName;
    vProp=proj.getProperties(args);
    Double f=(Double)vProp.elementAt(15);
    UAech=f.doubleValue();

    amontChaud.getProperties();
    avalChaud.getProperties();
    amontFroid.getProperties();
    avalFroid.getProperties();

    //initialisations du TechnoDesign
    technoEchangeur.UA=UAech;
    technoEchangeur.makeDesign();

    //affichages
    U_value.setText(Util.aff_d(technoEchangeur.getU(),4));
    UAech_value.setText(Util.aff_d(UAech,4));
    AechReel=Util.lit_d(technoEchangeur.ADesign_value.getText());
    AcalculatedEch_value.setText(Util.aff_d(AechReel,4));
}
```

The calculations here are very simple: using Project method getProperties(), the driver retrieves the values of UA and ΔH. The exchanger is then calculated by method makeDesign() and the results are displayed on the screen.

3.3.2.3 Backup

In this example, there are no particular backups to make considering constant thermal resistance of fouling. Standard methods for the backup of technological parameters will do.

Two ExtPilot methods, transferTechnoData() and setupTechnoDesigns(), are used to initialize the driver and technological screen while opening an existing project file.

The first method groups all lines in the project file on technological screens and loads them in the driver until it is built, and the second decodes these lines to perform its initialization, passing the values to the standard TechnoExch methods, which in turn call the FlowConfig ones.

The last line of setupTechnoDesigns(), proj.bindTechnoDesigns(vSettings), is used to link the TechnoDesign used by the driver with the core components, so they can be displayed from their screens and from the tables of the main technological and simulation screen.

4 OFF-DESIGN

The computer structure developed in order to perform technological design also allows to analyze the off-design operation of models created with Thermoptim.

This type of analysis includes, however, additional difficulties: they require the modeller to be able first to write the set of equations describing the coupling existing between the various components of the system studied, and second to find an appropriate resolution algorithm.

The cases we have treated have shown us that there are two major additional challenges:

- the first concerns the development of physical phenomena equations. The behavior of the different components must be analyzed carefully and modeled correctly, which may be far from simple. We propose in the examples posted on the Thermoptim-Unit portal a number of models, but variants are also possible, and we have not covered all interesting cases;
- the second corresponds to the resolution, usually numerical, of the model equations, which requires first to find a suitable algorithm, and second to initialize it properly.

As our intention is primarily focused on applied thermodynamics, we mainly concentrated on the first difficulty. Numerical tools that we offer use either Thermoptim own libraries, to perform simple searches by dichotomy, or generic, like minPack, which is a set of classes allowing to make nonlinear optimization, in particular seek the solution of systems of equations. It will be presented in Section 4.3.

We will start initially by treating a simple example that does not pose any problem of numerical resolution and explain the code of the driver class.

4.1 Example

To illustrate the ability of Thermoptim to perform off-design calculations, we will study the behavior of a volumetric air compressor that fills a compressed air storage volume at variable pressure. The compressed air is cooled before storage with a water exchanger of the kind just presented.

The system can be easily modeled in Thermoptim and leads to a diagram like Figure 4.1, which differs from that studied in the previous example by adding the compressor.

The technological design screen of the compressor is given in Figure 4.2. The heat exchanger is similar to the previous one. They correspond to the physical models presented in Section 3.1 of this manual.

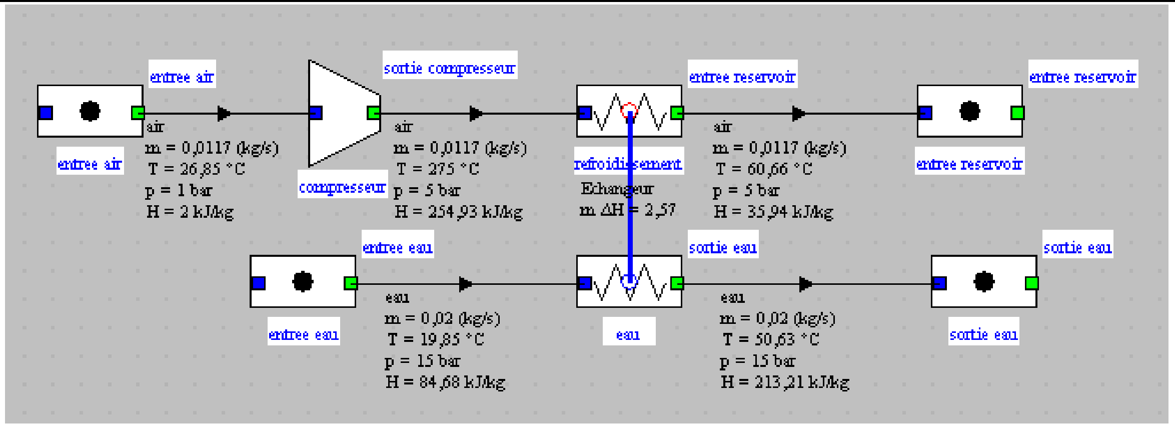
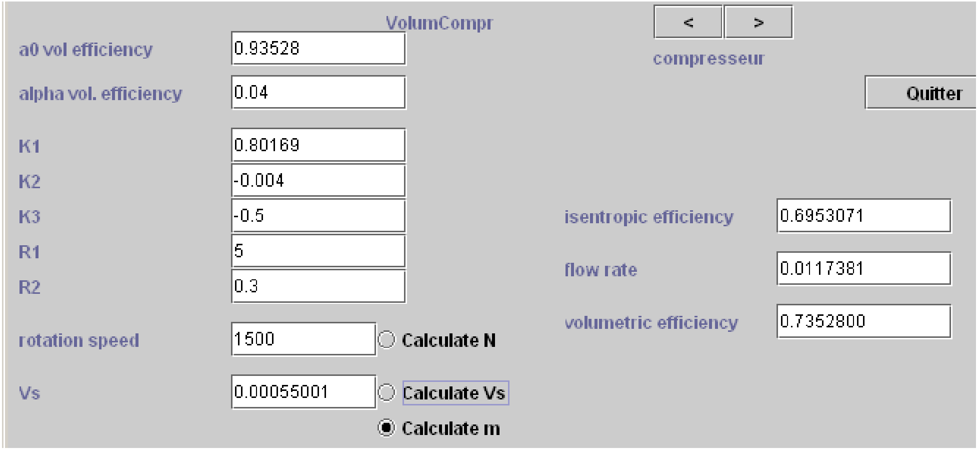


Figure 4.1 : Example of compressor cooling

Note, as we have not yet said that double-clicking the component name (here "compressor" located under the small arrows in the upper right) provides access to its phenomenological thermodynamic screen.



a0 vol efficiency: 0.93528
alpha vol. efficiency: 0.04
K1: 0.80169
K2: -0.004
K3: -0.5
R1: 5
R2: 0.3
rotation speed: 1500 ○ Calculate N
Vs: 0.00055001 ○ Calculate Vs
● Calculate m
isentropic efficiency: 0.6953071
flow rate: 0.0117381
volumetric efficiency: 0.7352800

Figure 4.2 : Compressor screen

4.1.1 Results

Once the driver made, it is very easy to make the compression ratio vary in order to get the evolution of the main variables when the pressure of the tank changes. They can be processed with the Thermoptim simulation files Excel post-treatment macro presented in Volume 1 of the reference manual. Simply save the project file under a different name after each simulation, then load these files into the macro and extract the interesting values.

Figure 4.3 shows, as a function of the storage pressure, changes in the isentropic efficiency and compression work, intake air flow, temperature of air entering the tank, exchanger load and U value.

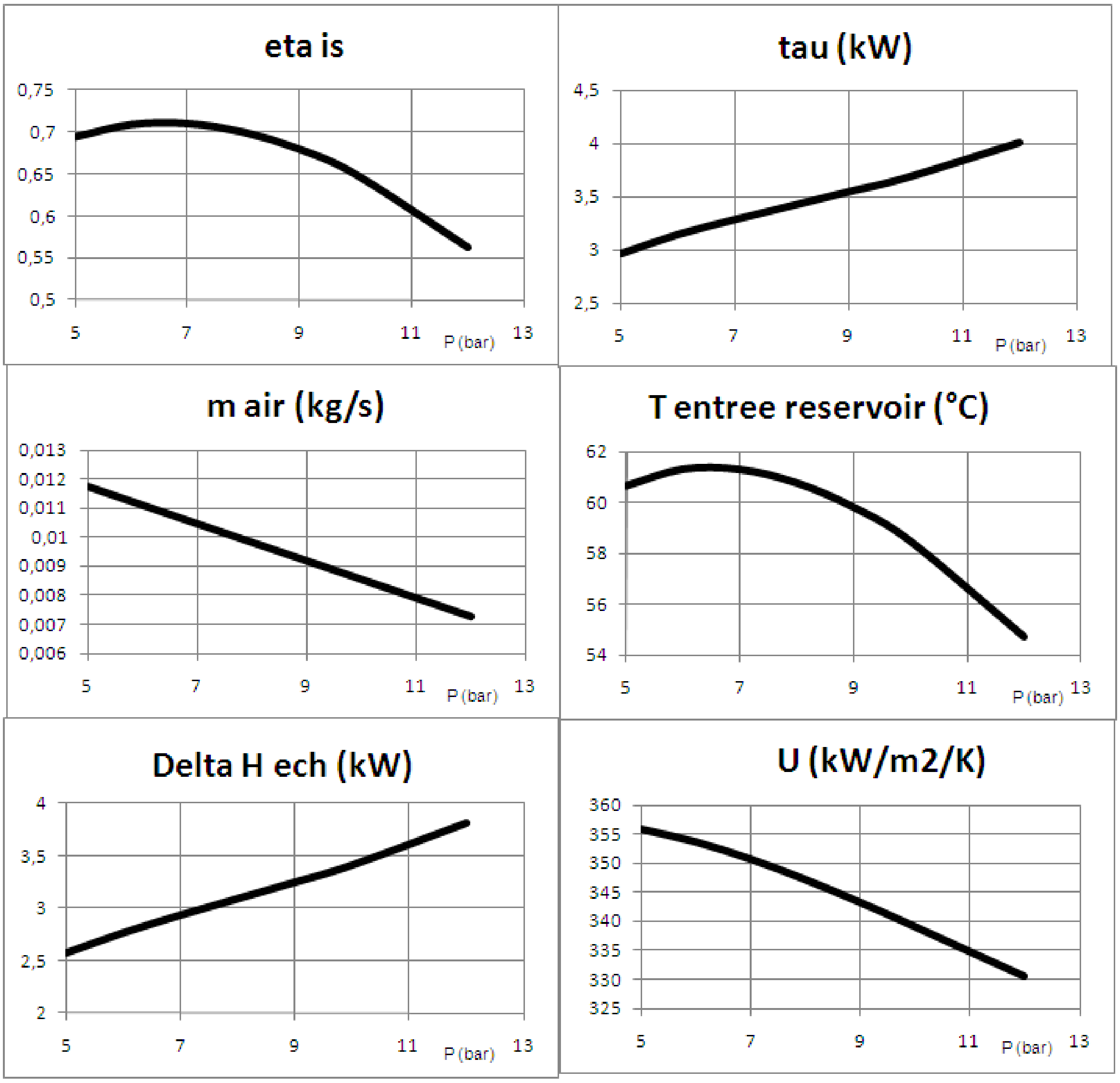
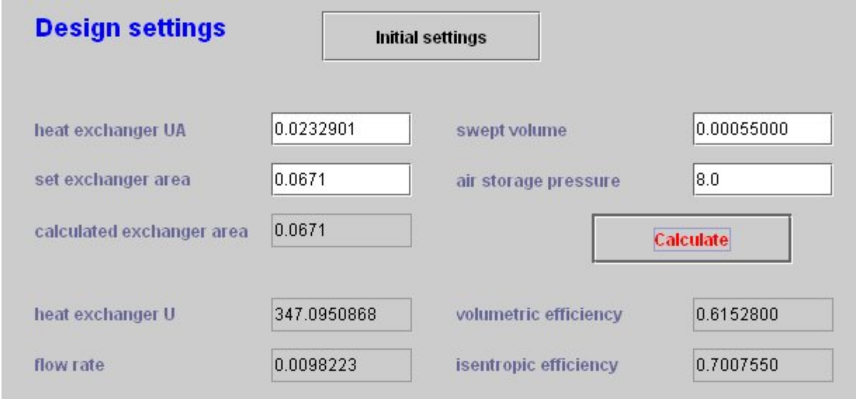


Figure 4.3 : Simulation results

4.1.2 Driver implementation

The driver class is called VsCompressorDriver and its type is "Vs compressor driver". Its interface being simple and classic, we do not break it here.

The driver screen is shown in Figure 4.4.



heat exchanger UA	0.0232901	swept volume	0.00055000
set exchanger area	0.0671	air storage pressure	8.0
calculated exchanger area	0.0671		
heat exchanger U	347.0950868	volumetric efficiency	0.6152800
flow rate	0.0098223	isentropic efficiency	0.7007550

Figure 4.4 : Driver screen

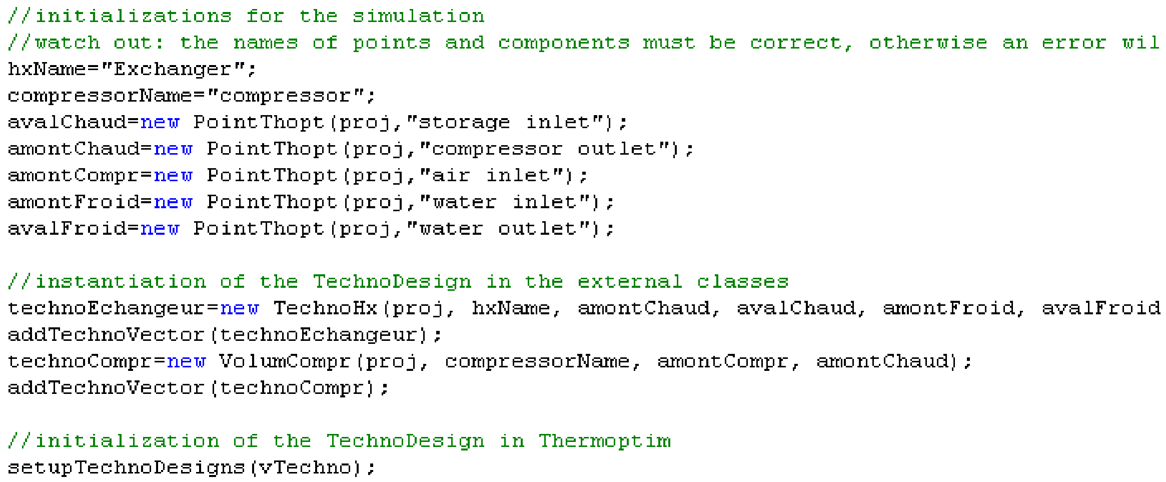
To write the relevant class, we start from the exchanger driver one, and complement it on two points:

- first by instantiating and initializing the compressor technological screen, as for the heat exchanger;

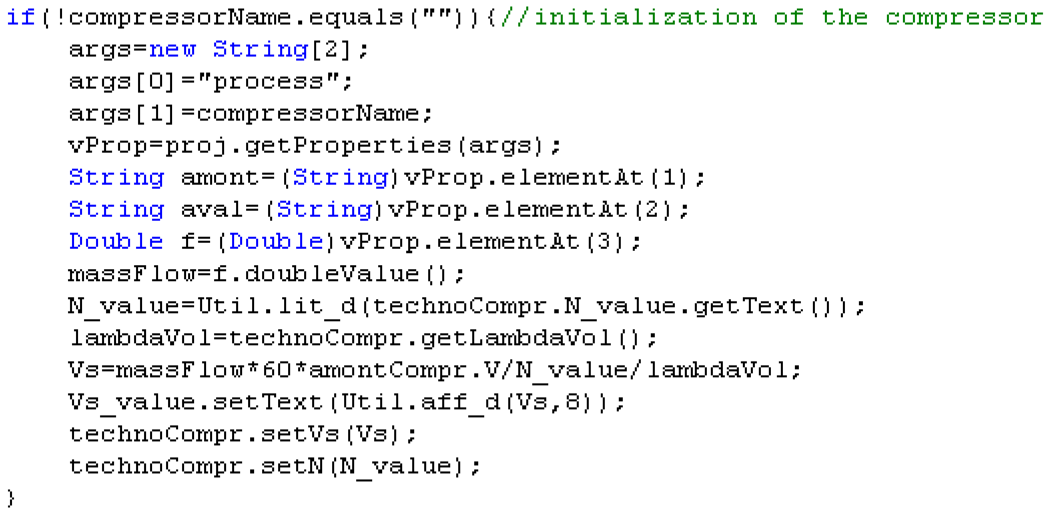
- second by introducing a button "Calculate" and defining calculations and changes in the simulator settings which should be carried out when the downstream pressure varies.

4.1.2.1 Initializations

During initialization, after the PointThopt and the two TechnoDesign have been constructed, the compressor swept volume Vs required to obtain the desired flow is determined on the basis of technological screen settings.



```
//initializations for the simulation
//watch out: the names of points and components must be correct, otherwise an error wil
hxName="Exchanger";
compressorName="compressor";
avalChaud=new PointThopt(proj,"storage inlet");
amontChaud=new PointThopt(proj,"compressor outlet");
amontCompr=new PointThopt(proj,"air inlet");
amontFroid=new PointThopt(proj,"water inlet");
avalFroid=new PointThopt(proj,"water outlet");

//instantiation of the TechnoDesign in the external classes
technoEchangeur=new TechnoHx(proj, hxName, amontChaud, avalChaud, amontFroid, avalFroid
addTechnoVector(technoEchangeur);
technoCompr=new VolumCompr(proj, compressorName, amontCompr, amontChaud);
addTechnoVector(technoCompr);

//initialization of the TechnoDesign in Thermoptim
setupTechnoDesigns(vTechno);
```



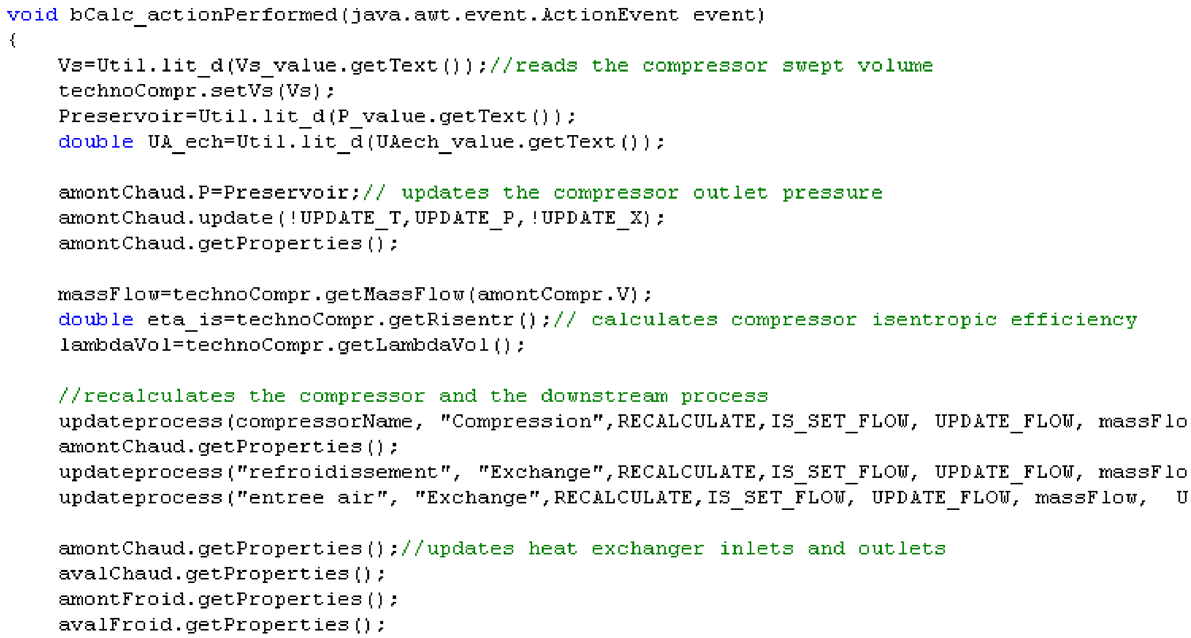
```
if(!compressorName.equals("")){//initialization of the compressor
    args=new String[2];
    args[0]="process";
    args[1]=compressorName;
    vProp=proj.getProperties(args);
    String amont=(String)vProp.elementAt(1);
    String aval=(String)vProp.elementAt(2);
    Double f=(Double)vProp.elementAt(3);
    massFlow=f.doubleValue();
    N_value=Util.lit_d(technoCompr.N_value.getText());
    lambdaVol=technoCompr.getLambdaVol();
    Vs=massFlow*60*amontCompr.V/N_value/lambdaVol;
    Vs_value.setText(Util.aff_d(Vs,8));
    technoCompr.setVs(Vs);
    technoCompr.setN(N_value);
}
```

4.1.2.2 Calculations

The calculations are made as follows:

- first initialize the swept volume and update the compressor output pressure
- calculate its volumetric and isentropic efficiencies, determine the mass flow rate transferred and propagate it upstream and dowstream
- recalculate the compressor and its downstream process, knowing that, set as isobaric, it propagates the new pressure
- update exchanger inlets and outlets and then recalculate the off-design operation after having updated the air heat flow rate
- update the simulator and recalculate the project several times to ensure the stabilization of values.

This example illustrates even better than its predecessor the interest of the PointThopt used to communicate between the driver and the simulator. The syntax of updates is much more readable than when using only Project methods getProperties() and updatePoint().



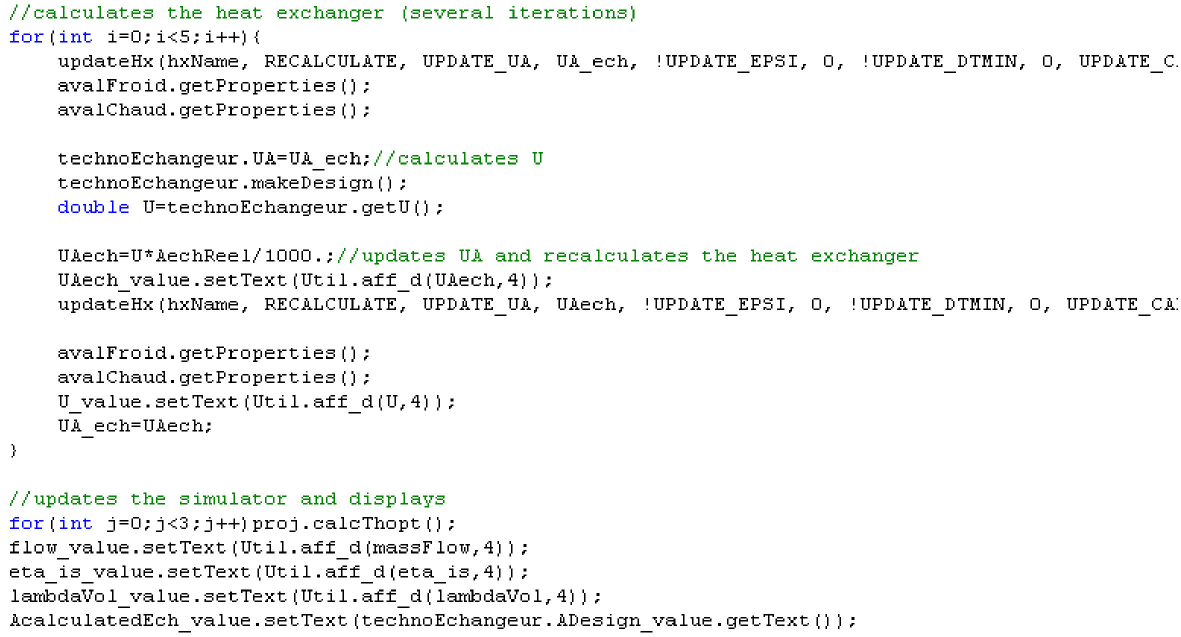
```
void bCalc_actionPerformed(java.awt.event.ActionEvent event)
{
    Vs=Util.lit_d(Vs_value.getText());//reads the compressor swept volume
    technoCompr.setVs(Vs);
    Preservoir=Util.lit_d(P_value.getText());
    double UA_ech=Util.lit_d(UAech_value.getText());

    amontChaud.P=Preservoir;// updates the compressor outlet pressure
    amontChaud.update(!UPDATE_T,UPDATE_P,!UPDATE_X);
    amontChaud.getProperties();

    massFlow=technoCompr.getMassFlow(amontCompr.V);
    double eta_is=technoCompr.getRisentr();// calculates compressor isentropic efficiency
    lambdaVol=technoCompr.getLambdaVol();

    //recalculates the compressor and the downstream process
    updateprocess(compressorName, "Compression",RECALCULATE,IS_SET_FLOW, UPDATE_FLOW, massFlo
    amontChaud.getProperties();
    updateprocess("refroidissement", "Exchange",RECALCULATE,IS_SET_FLOW, UPDATE_FLOW, massFlo
    updateprocess("entree air", "Exchange",RECALCULATE,IS_SET_FLOW, UPDATE_FLOW, massFlow,  U

    amontChaud.getProperties();//updates heat exchanger inlets and outlets
    avalChaud.getProperties();
    amontFroid.getProperties();
    avalFroid.getProperties();
```

The calculation of the compressor is done by methods getRisentr() and getLambdaVol() introduced previously. Method updateprocess() modifies the compressor flow and isentropic efficiency and then recalculates it. Its outlet point, called here "amontChaud" because it corresponds to the heat exchanger upstream hot fluid is then updated.

The calculation of the heat exchanger is made as follows: first we make a calculation using method updateHx() by setting the UA value read at the screen, UA_ech (heat exchanger is set for the off-design calculation mode so that the value of UA is taken into account). This calculation allows the exchanger to initialize the new operating conditions.

We then call method makeDesign() of TechnoDesign, which updates the value of U. The real UA is obtained by multiplying the new U with the initial value of A (AechReel), which allows the exchanger to recalculate properly.

Since U depends on the average temperatures of fluids, and therefore those of outlets, we iterate five times the calculations to ensure proper stabilization, resetting each time UA_ech.



```
//calculates the heat exchanger (several iterations)
for(int i=0;i<5;i++){
    updateHx(hxName, RECALCULATE, UPDATE_UA, UA_ech, !UPDATE_EPSI, 0, !UPDATE_DTMIN, 0, UPDATE_C
    avalFroid.getProperties();
    avalChaud.getProperties();

    technoEchangeur.UA=UA_ech;//calculates U
    technoEchangeur.makeDesign();
    double U=technoEchangeur.getU();

    UAech=U*AechReel/1000.;//updates UA and recalculates the heat exchanger
    UAech_value.setText(Util.aff_d(UAech,4));
    updateHx(hxName, RECALCULATE, UPDATE_UA, UAech, !UPDATE_EPSI, 0, !UPDATE_DTMIN, 0, UPDATE_CA

    avalFroid.getProperties();
    avalChaud.getProperties();
    U_value.setText(Util.aff_d(U,4));
    UA_ech=UAech;
}

//updates the simulator and displays
for(int j=0;j<3;j++)proj.calcThopt();
flow_value.setText(Util.aff_d(massFlow,4));
eta_is_value.setText(Util.aff_d(eta_is,4));
lambdaVol_value.setText(Util.aff_d(lambdaVol,4));
AcalculatedEch_value.setText(technoEchangeur.ADesign_value.getText());
```

4.1.2.3 Backup

Backups and updates on project loadings are similar to those of class PiloteEchangeur. Method setupPilot() has been supplemented to reflect the existence of the compressor.

4.2 Using the model to simulate the filling of a compressed air storage

The results obtained can be used to simulate the filling of a compressed air storage. For this simulation, we develop a second model, solved with Excel, with the following equations:

- the air mass M contained in the storage is equal to the initial mass plus the the integral of the mass flow
- the internal energy U is equal to the initial internal energy plus the integral of the product of the flow by the enthalpy of air leaving the cooler, less the integral of losses by convection with ambient air
- the storage temperature is inferred from its internal energy
- the pressure is then calculated by the ideal gas law.

To find the flow and the enthalpy of the air stored, just make polynomial regressions from Thermoptim simulations.
To find the flow, the compression work and the temperature of the air entering storage, simply do polynomial regressions from Thermoptim simulations. Equations obtained, function of the compression ratio r, are:

$$\dot{m} = - 0{,}0006\ r + 0{,}0149$$

$$\tau = 0{,}0019\ r^3 - 0{,}0484\ r^2 + 0{,}5322\ r + 1{,}2806$$

$$Tair = 0{,}01\ r^3 - 0{,}4735\ r^2 + 4{,}9142\ r + 46{,}699$$

The look of the results is given below, for a half m3 storage (diameter 80 cm, length 1 m), powered by a compressor of Vs = 0.525 l swept volume. The pressure and temperature in storage, its mass and the compressor workload are shown in figure 4.5.

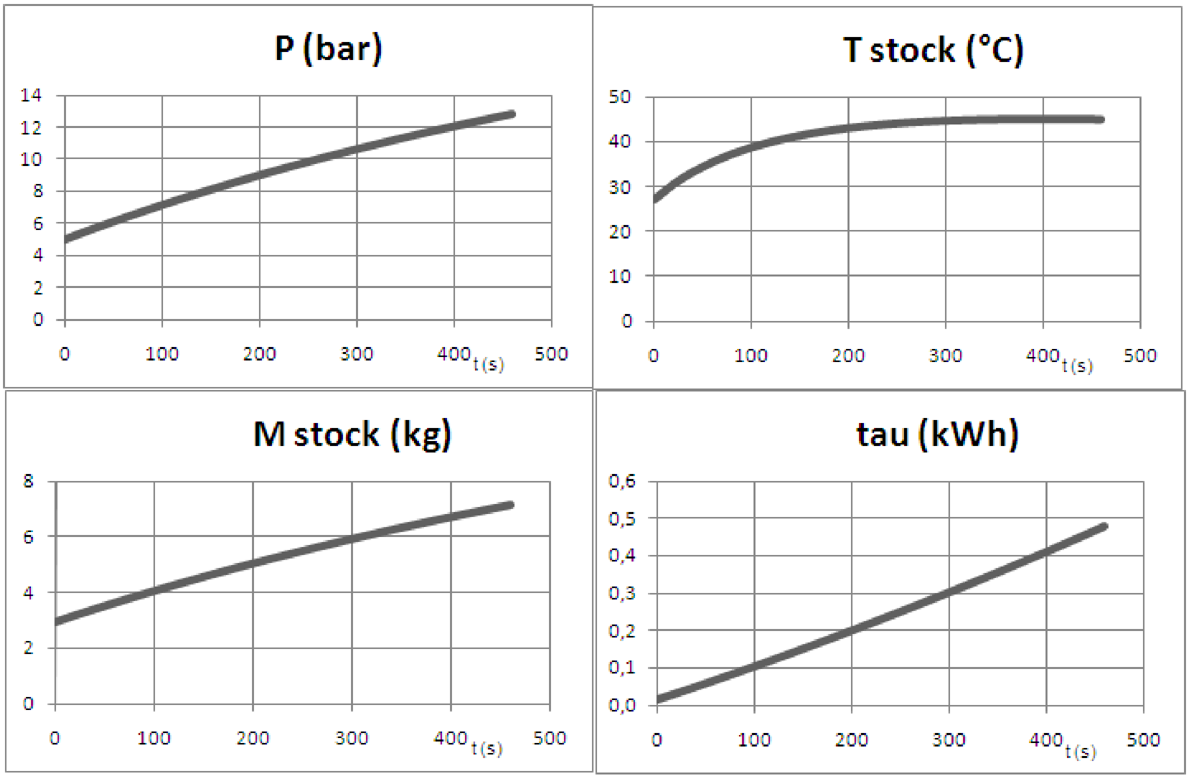


Figure 4.5 : Filling the compressed air storage

This example has taught you how to write a driver to simulate the behavior in off-design operation regime of a relatively simple thermodynamic system. For further investigation, we advise you to study the code of a cooling machine driver available on the Thermoptim-UNIT portal [2].

4.3 Use of minpack solver for solving systems of nonlinear equations

In many cases, the equations describing the off-design behavior of an energy system are nonlinear, so that their resolution is a difficult problem, particularly when the number of unknowns is high.

4.3.1 Presentation of minPack

Based on the method of Levendberg-Marquardt minPack is a set of algorithms developed in Fortran and then translated to Java. This method combines the Gauss-Newton and gradient descent methods. Its main interest is to be very robust and not to require initialization by an approximate solution.

Note that minPack is actually a set of minimization algorithms that can be used to find the minimum of the L2 residuals ||F(X)|| a set of m non-linear equations in n unknowns F(X).

When n is equal to m, minPack can be used to solve the system of equations F(X) = 0, or at least seek a vector X that is as close as possible to the solution.

You can also use minPack to identify a set of n parameters to fit a nonlinear equation on a set of m data.

4.3.2 Implementation of minPack

The set of classes required is included in library extBib.zip which must be declared in the classpath.

The implementation of Java minPack is done using an interface called optimization.Lmdif_fcn, which forces the calling class to have a method called fcn().

This method fcn() receives as key arguments a vector (array x[n]) containing the variables and a vector (array fvec[m]) referring to residues of the functions one seeks to set to zero. As we have indicated, number m may exceed the number of variables n, but it must be the same if we seek the solution of a system of equations.

Guiding the algorithm is done in practice by playing on two accuracy criteria, one on the residuals, and the other on the accuracy of the calculation of partial derivatives, estimated by finite differences.

4.3.3 Example

To illustrate the use of minPack, we have written a test class called TestMinPack, which solves the equation system corresponding to the intersection of a circle and a straight line. The code is as follows:

```
int info[] = new int[2];
int m = 2;//système de deux équations / / system of two equations
int n = 2;//à deux inconnues / / with two unknowns
int iflag[] = new int[2];
double fvec[] = new double[m+1];//vecteur des résidus / / vector of residuals
double x[] = new double[n+1];
double residu0;//norme L2 initiale
double residu1;//norme L2 finale

System.out.print("\n\n\n\n\n problem dimensions:  " + n + "  " + m + "\n");

//initialisation des inconnues / / Initialization of the unknowns
x[1] = 1;
```

---

[2] http://www.thermoptim.org/sections/logiciels/thermoptim/documentation/pilote-pour-cycle

```
x[2] = 0;

iflag[1] = 0;

testMinPack.fcn(m,n,x,fvec,iflag);//premier appel pour calcul norme L2 initiale / / first call for calculating initial L2
//norme L2 initiale
residu0 = optimization.Minpack_f77.enorm_f77(m,fvec);

testMinPack.nfev = 0;
testMinPack.njev = 0;

double epsi=0.0005;//précision globale demandée sur la convergence  / precision required on the overall convergence
double epsfcn = 1.e-6;//précision calcul des différences finies / / precision calculus of finite differences

//appel à minPack / / Call for minpack
optimization.Minpack_f77.lmdif2_f77(testMinPack, m, n, x, fvec, epsi, epsfcn, info);

//norme L2 finale
residu1 = optimization.Minpack_f77.enorm_f77(m,fvec);

//affichage des résultats    / / Display results
System.out.println("\n Initial L2 norm of the residuals: " + residu0 +
        "\n Final L2 norm of the residuals: " + residu1 +
        "\n Number of function evaluations: " + testMinPack.nfev +
        "\n Number of Jacobian evaluations: " + testMinPack.njev +
        "\n Info value: " + info[1] );
System.out.println();
System.out.println("precision: \t" + residu1);
for(int i=1;i<=n;i++){//affichage de la solution
   System.out.println("x["+i+"] \t" + x[i]);
}
```

function fcn is defined as follows:

```
public void fcn(int m, int n, double x[], double fvec[], int iflag[]) {

            if (iflag[1]==1) this.nfev++;
            if (iflag[1]==2) this.njev++;

            fvec[1] =x[1]*x[1]+x[2]*x[2]-1;
            fvec[2] =3*x[1]+2*x[2]-1;
}
```

The results obtained are as follows, for initialization x[1] = 1, x[2] = 0 :

```
problem dimensions:  2  2

 Initial L2 norm of the residuals: 2.0
 Final L2 norm of the residuals: 2.39665398638067E-10
 Number of function evaluations: 6
 Number of Jacobian evaluations: 10
 Info value: 2

precision:      2.39665398638067E-10
x[1]    0.7637079407212384
x[2]    -0.6455619110818576
```

for initialization x[1] = 0, x[2] = 0 :

```
problem dimensions:  2  2

 Initial L2 norm of the residuals: 1.4142135623730951
 Final L2 norm of the residuals: 3.853333208070353E-10
 Number of function evaluations: 9
 Number of Jacobian evaluations: 12
 Info value: 2

precision:          3.853333208070353E-10
x[1]      -0.3021694793631984
x[2]      0.9532542190447976
```

This example illustrates on the hand how minPack can be used, but also the importance of initializing well the problem. In our case, the problem has two solutions, but the algorithm is satisfied with the first that it finds, which is the closest to the starting value.

APPENDIX : Classes ExtPilot, PointThopt, CorpsThopt

In this appendix, we give some indications on the three classes ExtPilot, PointThopt and CorpsThopt that have been defined to facilitate the creation of advanced external classes, including drivers.

Class ExtPilot

This is the superclass of all drivers. To secure the setting of the different methods allowing to update the core Thermoptim objects it offers, it defines a number of directly understandable booleans:

boolean RECALCULATE=true, UPDATE_T=true, UPDATE_P=true, UPDATE_X=true, UPDATE_ETA=true, UPDATE_UA=true, UPDATE_EPSI=true, UPDATE_FLOW=true, IS_SET_FLOW=true, UPDATE_DTMIN=true;

In this way, the following code updating a point:

avalFroid.update(UPDATE_T,!UPDATE_P,!UPDATE_X);

reads as only update the avalFroid point temperature, which is much more readable than :

avalFroid.update(true, false , false);

public void **updateprocess**(String name, String type, boolean recalculate, boolean isSetFlow, boolean updateFlow, double flow,
boolean updateParam1, double param1, boolean updateParam2, double param2)

Available with several signatures, this method updates and recalculates a process. If recalculate is true, it is recalculated, if isSetFlow if true, its flow is set, if updateFlow is true, its flow is set to flow, if updateParam is true, the parameter value is set. The meaning of arg depends on the type and can be solved by referring to the Project method updateProcess(), as defined in Volume 3 Reference Manual.

For example, the following code updates the process name compressorName, of the Compression type, request the recalculation, sets the flow rate by changing its value, and modifies the isentropic efficiency:

```
        updateprocess(compressorName, "Compression",RECALCULATE,IS_SET_FLOW, UPDATE_FLOW,
massFlow,  UPDATE_ETA, eta_is);
```

Similarly, methods for updating and recalculating for heat exchangers and nodes exist:

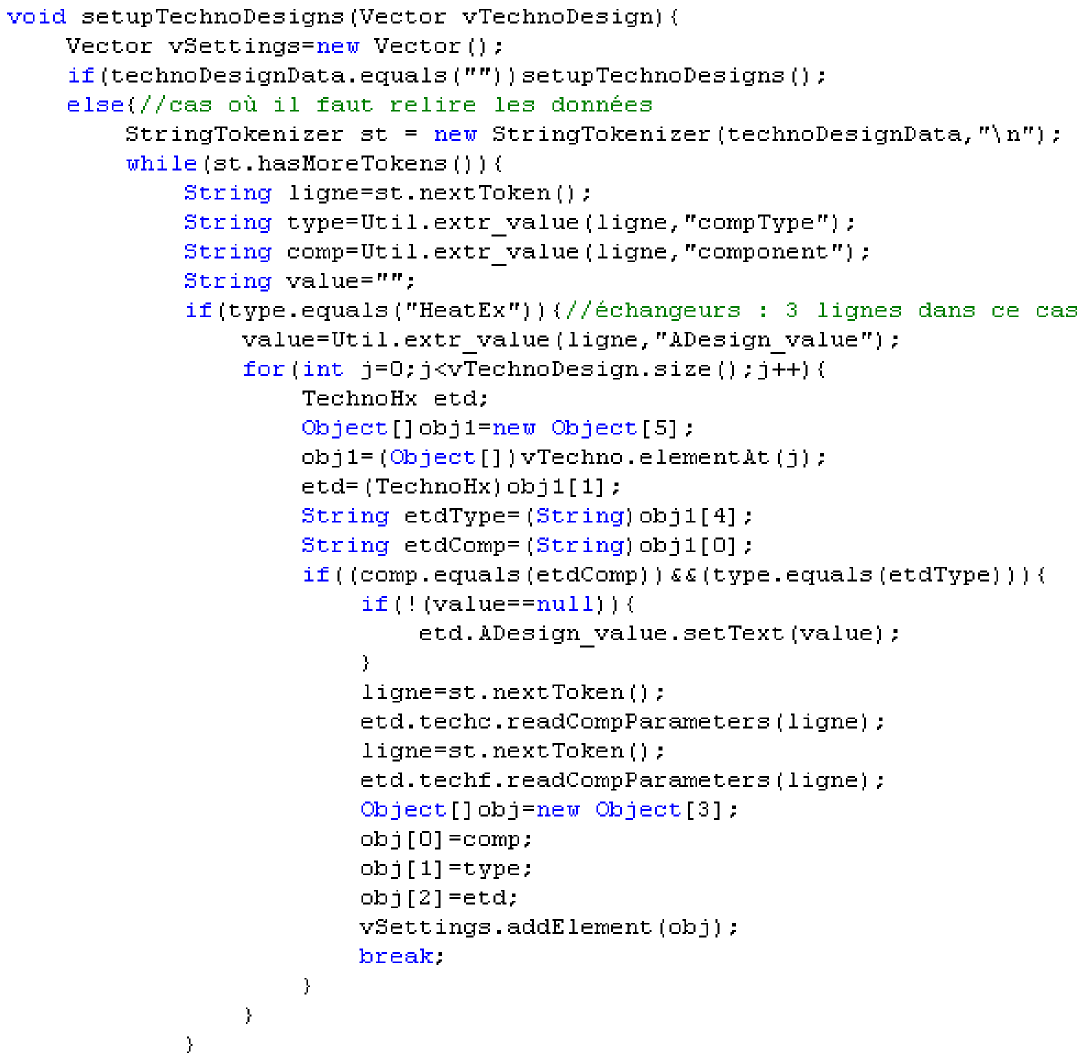
public void **updateHx**(String name, boolean recalculate, boolean updateUA, double UA,
boolean updateEpsi, double epsi, boolean updateDTmin, double DTmin)

public void **updateNode**(String name, boolean recalculate, boolean updateEffectiveness, double epsi)

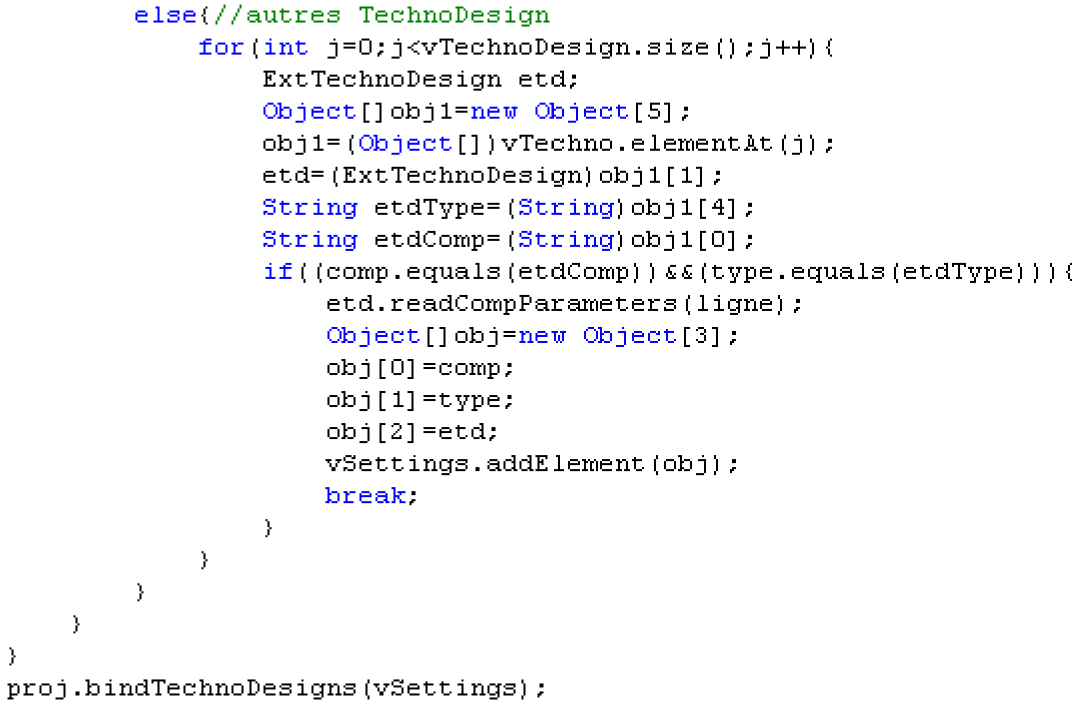
Both methods transferTechnoData () and setupTechnoDesigns () are used to initialize the driver and technological screen while opening an existing project file.

The first method includes all lines in project file on technological screens and loads them in the driver when it is built, and the second decodes these lines to perform its initialization, calling the standard TechnoExch methods, which call on FlowConfig.

The last setupTechnoDesigns()line proj.bindTechnoDesigns(vSettings), is used to link the TechnoDesign used by the driver with the core components, so they can be displayed from their screens and global tables of the technological and simulation screen.



```
void setupTechnoDesigns(Vector vTechnoDesign){
    Vector vSettings=new Vector();
    if(technoDesignData.equals(""))setupTechnoDesigns();
    else{//cas où il faut relire les données
        StringTokenizer st = new StringTokenizer(technoDesignData,"\n");
        while(st.hasMoreTokens()){
            String ligne=st.nextToken();
            String type=Util.extr_value(ligne,"compType");
            String comp=Util.extr_value(ligne,"component");
            String value="";
            if(type.equals("HeatEx")){//échangeurs : 3 lignes dans ce cas
                value=Util.extr_value(ligne,"ADesign_value");
                for(int j=0;j<vTechnoDesign.size();j++){
                    TechnoHx etd;
                    Object[]obj1=new Object[5];
                    obj1=(Object[])vTechno.elementAt(j);
                    etd=(TechnoHx)obj1[1];
                    String etdType=(String)obj1[4];
                    String etdComp=(String)obj1[0];
                    if((comp.equals(etdComp))&&(type.equals(etdType))){
                        if(!(value==null)){
                            etd.ADesign_value.setText(value);
                        }
                        ligne=st.nextToken();
                        etd.techc.readCompParameters(ligne);
                        ligne=st.nextToken();
                        etd.techf.readCompParameters(ligne);
                        Object[]obj=new Object[3];
                        obj[0]=comp;
                        obj[1]=type;
                        obj[2]=etd;
                        vSettings.addElement(obj);
                        break;
                    }
                }
            }
```



```
        else{//autres TechnoDesign
            for(int j=0;j<vTechnoDesign.size();j++){
                ExtTechnoDesign etd;
                Object[]obj1=new Object[5];
                obj1=(Object[])vTechno.elementAt(j);
                etd=(ExtTechnoDesign)obj1[1];
                String etdType=(String)obj1[4];
                String etdComp=(String)obj1[0];
                if((comp.equals(etdComp))&&(type.equals(etdType))){
                    etd.readCompParameters(ligne);
                    Object[]obj=new Object[3];
                    obj[0]=comp;
                    obj[1]=type;
                    obj[2]=etd;
                    vSettings.addElement(obj);
                    break;
                }
            }
        }
    }
}
proj.bindTechnoDesigns(vSettings);
```

Class PointThopt

This class creates kinds of external clones of core Thermoptim points, in order to have easy access to their values, which are not otherwise directly accessible. It provides more comfort and clarity than does the use of Project methods getProperties() and updatePoint(), documented in Volume 3 Reference Manual. It includes double values that store equivalents of core state variables:

```
double W,Epsi,QPrime,Tprime,Tr,VPrime,Cond, M_sec, corrFactor;
 CorpsThopt corps;
```

During construction, it specifies the reference to the project and the name of the point in the simulator, which allows Thermoptim to know which point is concerned. Caution, if an error occurs at this level, the PointThopt cannot be properly instantiated.

```
public PointThopt(Projet proj, String name){
        this.proj=proj;
        this.name=name;
        try{
           getProperties();
        }
        catch(Exception e){
           String msg = "Error constructing the PointCorps name: "+ name;
           JOptionPane.showMessageDialog(new JFrame(), msg);
           e.printStackTrace();
        }
        corps=new CorpsThopt(proj, nomCorps,lecorps);
}
```

PointThopt also offers methods to update its simulator equivalent, based on the same principle as those of ExtPilot with signatures depending on the number of values to change.

```
   public void update(boolean updateT, boolean updateP, boolean updateX, boolean updateCorrFactor, boolean
melHum, String task, double value)
```

A most common lighter version served as an example explaining the use of explicit ExtPilot booleans:

```
   public void update(boolean updateT, boolean updateP, boolean updateX){
      update(updateT, updateP, updateX, false, false, "", 0.);
   }
```

Class CorpsThopt

This class creates kinds of clones of core Thermoptim substances, to have easy access to their values, which are not otherwise directly accessible. It provides more comfort and clarity than does the use of Project methods getProperties() and updateSubstance(), documented in Volume 3 Reference Manual. It has double variables that store the equivalent of the core state variables:

```
public double T,P,X,V,U,H,S,M,M_sec,TC,PC,VC;
```

During construction, it specifies the reference to the project and the name of the substance in the simulator, which allows Thermoptim to know which substance is concerned. Caution, if an error at this level, the CorpsThopt cannot be properly instantiated.

```
    public CorpsThopt(Projet proj, String name, Corps lecorps){
       this.proj=proj;
       this.name=name;
       this.lecorps=lecorps;
    }
```

An instantiation example is given in the PointThopt constructor.

Mmethod getSubstProperties() allows to update the values after a calculation on variable lecorps. The example below shows using a CorpsThopt using PointThopt "amont":

```
CorpsThopt corps=new CorpsThopt(proj,amont.nomCorps, amont.lecorps);
corps.lecorps.CalcPropCorps(amont.T,amont.P,1.);
corps.getSubstProperties();
```

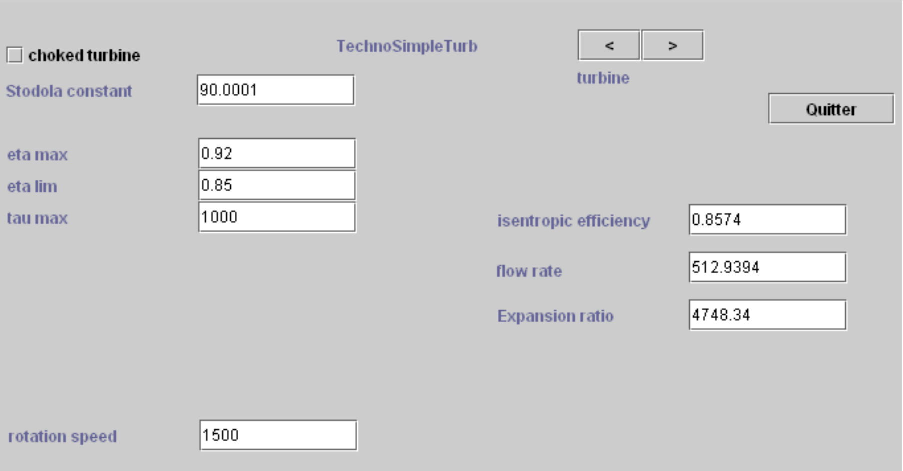
Usual functions are then directly accessible: for example, enthalpy is given by corps.H.

CLASSES FOR TECHNOLOGICAL DESIGN

The classes for compressors and exchangers have been presented Section 3.2. To introduce new classes, just subclass existing ones, or create new ones based on the same model and place them in extThopt.zip or extUser.zip.

Classes for turbines

Modeling turbine off-design operation is a problem that can be addressed with varying levels of difficulty. Therefore we implemented a series of different models, to graduate the approach depending on the available data and the the user level:



☐ choked turbine

Stodola constant: 90.0001

eta max: 0.92

eta lim: 0.85

tau max: 1000

isentropic efficiency: 0.8574

flow rate: 512.9394

Expansion ratio: 4748.34

rotation speed: 1500

Figure A.1 : Basic simple-stage turbine technological design screen

The basic class is TechnoSimpleTurb. It is based on the rule of the cone and strictly speaking only applies to a single-stage turbine:
- Class TechnoMultiStageTurb extends the previous one considering that the rule of the cone of the multi-stage turbine is the same as that of a single-stage turbine, the expansion ratio to take into account being the nth root of the total expansion ratio if n is the number of stages. If n = 1, the behavior is the same as that of the previous class;
- Class TechnoTurb extends the previous one, allowing to take into account both the existence of residual velocity losses (RVL) at the turbine outlet, and also a deterioration in isentropic efficiency in the wet zone following the Baumann rule;
- Class MultiStageMappedTurbine extends the previous one, the rule of the cone being this time replaced by a mapping represented by a numerical adjustment to twenty parameters.

TechnoSimpleTurb

This class defines the technological design parameters for turbines (figureA.1).

$$\frac{\dot{m}\sqrt{T_{in}}}{P_{in}} = Cste \qquad (A.1)$$

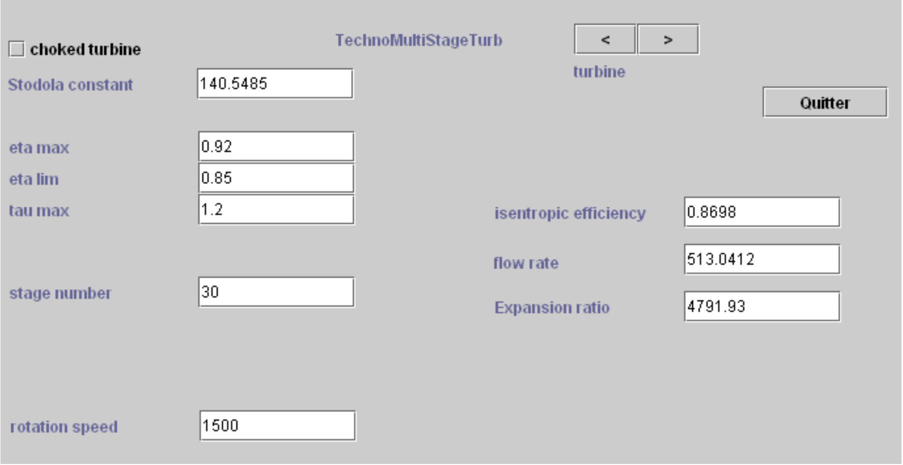
$$Tin\,\frac{\dot{m}^2}{K^2} = P_{in}^2 - P_{out}^2 \qquad (A.2)$$

The meaning of the fields is as follows:
- Stodola constant is the Stodola coefficient. If "choked turbine" is checked, the flow is regarded as shocking, and the formula used is (A.1). Otherwise, it is (A.2);
- where η is represented by an 3 parameter equation, eta max is the maximum value, eta lim the limit for the very high expansion rates, and tau max the abscissaof the maximum. If the first two values are equal, the isentropic efficiency is constant;
- rotationspeed is the speed of rotation ;

TechnoMultiStageTurb

The difference between its screen and the preceding is the introduction of a new field, representing the number of turbine stages (figure A2).

Stodola's formula taken into account is more general than (A2), and takes into account the polytropic coefficient of expansion.



☐ **choked turbine**

Stodola constant: 140.5485

eta max: 0.92

eta lim: 0.85

tau max: 1.2

stage number: 30

rotation speed: 1500

isentropic efficiency: 0.8698

flow rate: 513.0412

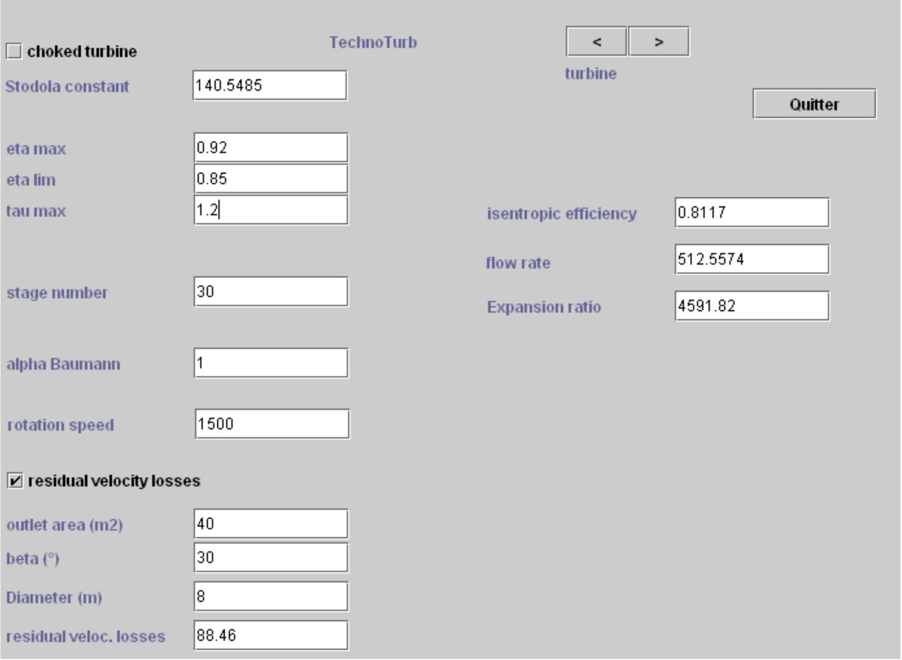
Expansion ratio: 4791.93

Figure A.2 : Multi-stage turbine technological design screen

TechnoTurb

Its screen (Figure A3) differs from the preceding by the several new fields. As mentioned above it takes into account the existence of residual velocity losses (RVL) at the turbine outlet, and a reduction of the isentropic efficiency in the wet zone, according to the Baumann rule (A3).

The values of residual velocity losses appear on the left of the screen.



☐ **choked turbine**

Stodola constant: 140.5485

eta max: 0.92

eta lim: 0.85

tau max: 1.2

stage number: 30

alpha Baumann: 1

rotation speed: 1500

☑ **residual velocity losses**

outlet area (m2): 40

beta (°): 30

Diameter (m): 8

residual veloc. losses: 88.46

isentropic efficiency: 0.8117

flow rate: 512.5574

Expansion ratio: 4591.82

Figure A.3 : Multi-stage turbine technological design screen

$$\eta_{hum} = \eta_{dry} (1 - \alpha (1 - x)) \qquad (A.3)$$

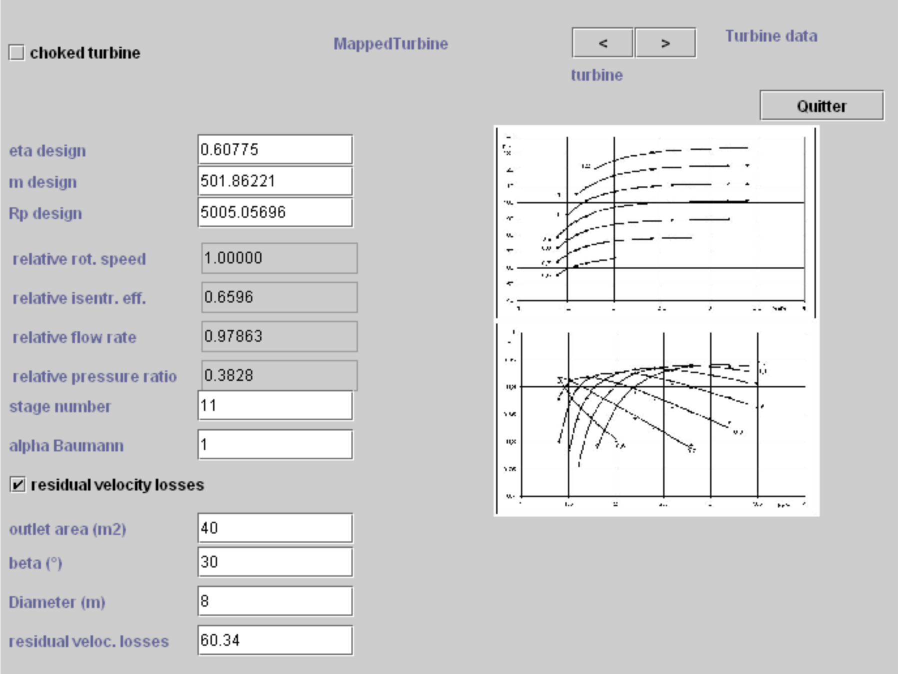
The meaning of the fields is as follows:

- alpha Baumann is the coefficient α of equation (A.3);
- for calculating residual velocity losses, it is necessary to provide the outlet section and the diameter of the turbine, as well as the output angle β.

Class MultiStageMappedTurbine

This class, which inherits from TechnoTurb defines the technological design parameters for turbines represented by detailed mapping, as defined in a modeling note [3].

The technological screen (figureA.4) has in its upper right a label ("Turbine data") which provides access by double-clicking to the screen displaying the series of coefficients describing flow rate and isentropic efficiency characteristics (class TurbineMapDataFrame, figureA.5).



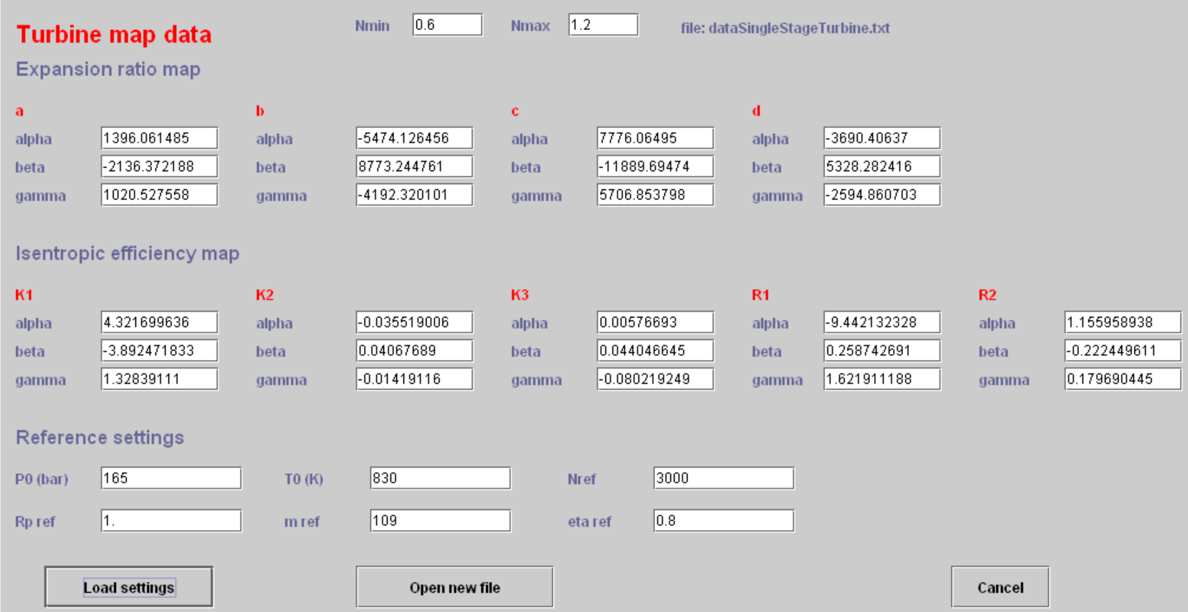
☐ choked turbine

eta design 0.60775
m design 501.86221
Rp design 5005.05696
relative rot. speed 1.00000
relative isentr. eff. 0.6596
relative flow rate 0.97863
relative pressure ratio 0.3828
stage number 11
alpha Baumann 1

☑ residual velocity losses

outlet area (m2) 40
beta (°) 30
Diameter (m) 8
residual veloc. losses 60.34

Figure A.4 : Turbine technological design screen with mapping



Turbine map data

Nmin 0.6
Nmax 1.2
file: dataSingleStageTurbine.txt

Expansion ratio map

	a		b		c		d
alpha	1396.061485	alpha	-5474.126456	alpha	7776.06495	alpha	-3690.40637
beta	-2136.372188	beta	8773.244761	beta	-11889.69474	beta	5328.282416
gamma	1020.527558	gamma	-4192.320101	gamma	5706.853798	gamma	-2594.860703

Isentropic efficiency map

	K1		K2		K3		R1		R2
alpha	4.321699636	alpha	-0.035519006	alpha	0.00576693	alpha	-9.442132328	alpha	1.155958938
beta	-3.892471833	beta	0.04067689	beta	0.044046645	beta	0.258742691	beta	-0.222449611
gamma	1.32839111	gamma	-0.01419116	gamma	-0.080219249	gamma	1.621911188	gamma	0.179690445

Reference settings

P0 (bar) 165
T0 (K) 830
Nref 3000
Rp ref 1.
m ref 109
eta ref 0.8

Figure A.5 : Turbine mapping setting screen

To the right of figureA.4 appears inset image corresponding to selected characteristics, if loaded. Otherwise the label "Turbine maps" allows to open by double click an image loading screen (class MapImage).

The data files and images of maps must be placed in the "maps" directory from which both classes work. Their names must be saved by the driver.

The mapping used here is expressed on a normalized flow. During design, we hold the nominal point of the mapping on that the expansion process (later, we should be able to deduce the size, but this not yet implemented), which provides the values "eta design","Rp design"and"m design"displayed in the left of the screen.

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[3] http://www.thermoptim.org/SE/seances/C01/ModelisationSimplifieeTurbomachines.pdf

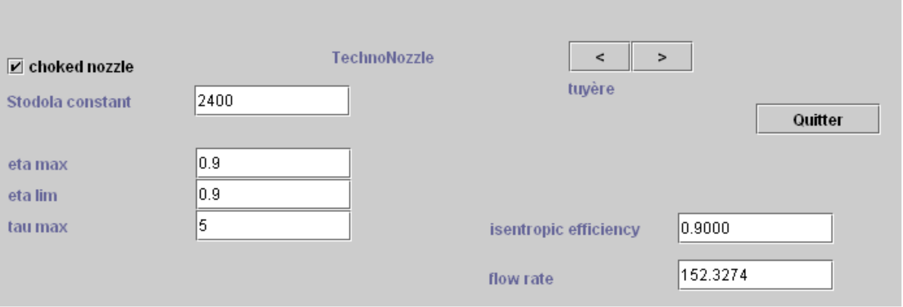
Below them appear dimensionless values needed to set the operating point on the mapping used. Their values are of course adjusted to the turbine inlet conditions.

The value of the rotation speed can be set from the driver screen if desired.

Class TechnoNozzle

This class defines the technological design parameters for nozzles (figureA.6).

In off-design operation, a nozzle can be modeled similarly to a turbine, and characterized by a Stodola constant and an isentropic efficiency. Its screen corresponds to the upper part of that of the simple-stage turbine.



☑ choked nozzle

Stodola constant 2400

eta max 0.9

eta lim 0.9

tau max 5

isentropic efficiency 0.9000

flow rate 152.3274

Figure A.6 : Design screen for a nozzle

Class TechnoTurboCompr

This class defines the technological design parameters for turbocompressors.

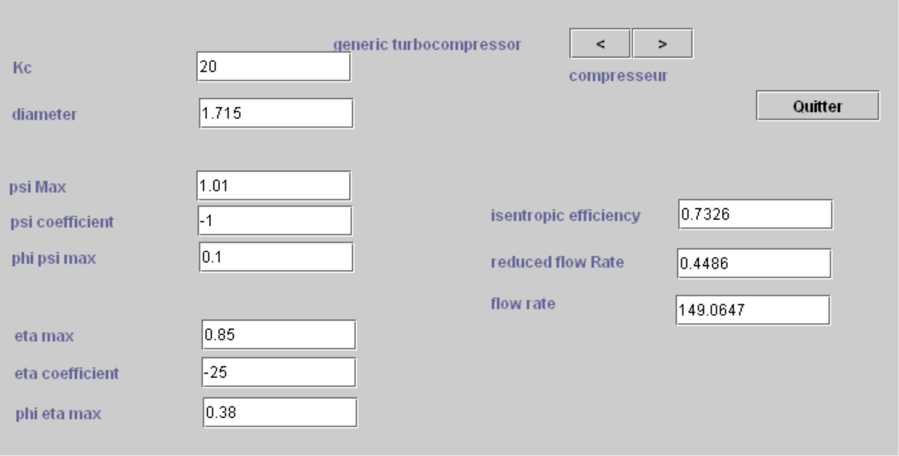
The technological screen (figureA.7) uses a series of coefficients describing both characteristics.

corrected reduced flow in the compressor $$mc = \frac{\dot{m}\, T_1}{K_c\, N\, P_1} \qquad \text{(A.4)}$$

reduced compressor charact. $$\psi = \psi_{coeff}\,(mc - \varphi\psi_{max})^2 + \psi_{max} \qquad \text{(A.5)}$$

The parameters to define are the following:

- Kc, compressor characteristic (equation (A.4));
- the compressor diameter;
- ψ is represented by a branch of a parabola, defined (equation (A.5)) by ψ_{max}, maximum value, ψ_{coeff} and $\varphi\psi_{max}$, abscissa of the maximum corrected flow mc;
- η is also represented by a branch of a parabola, defined by η_{max}, maximum value, η_{coeff} and $\varphi\eta_{max}$, abscissa of the maximum corrected flow mc.



Kc 20

diameter 1.715

psi Max 1.01

psi coefficient -1

phi psi max 0.1

eta max 0.85

eta coefficient -25

phi eta max 0.38

isentropic efficiency 0.7326

reduced flow Rate 0.4486

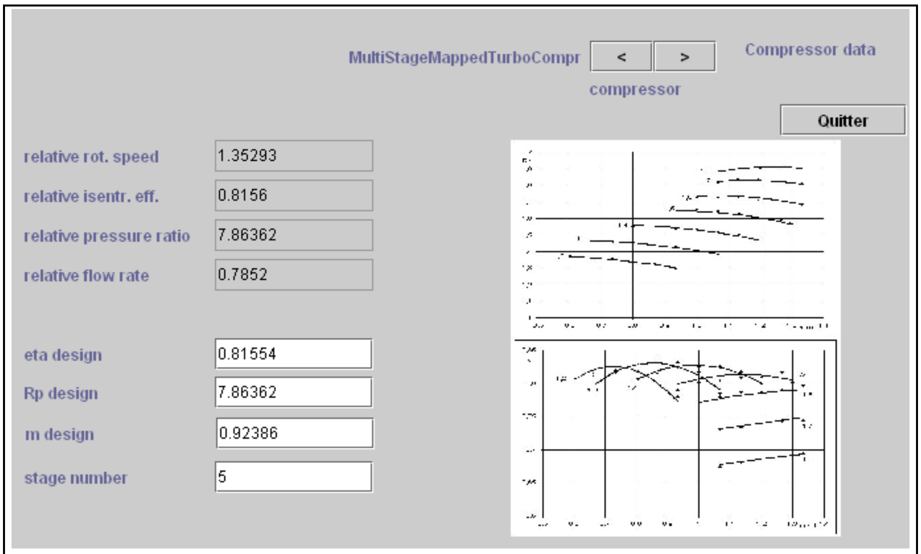
flow rate 149.0647

Figure A.7 : Turbocompressor technological design screen

The values of isentropic efficiency, flow and reduced mass flow appear on the right of the screen.

Class MultiStageMappedTurboCompr

This class, which inherits from TechnoTurboCompr defines the technological design parameters for turbocompressors represented by detailed mapping, as defined in the modeling note quoted above.



relative rot. speed: 1.35293
relative isentr. eff.: 0.8156
relative pressure ratio: 7.86362
relative flow rate: 0.7852
eta design: 0.81554
Rp design: 7.86362
m design: 0.92386
stage number: 5

Figure A.8 : Design screen of a turbocompressor with mapping

The technological screen (figureA.8) has in its upper right a label ("Compressor Data") which provides access by double-clicking to the screen displaying the series of coefficients describing flow rate and isentropic efficiency characteristics (class TurboComprMapDataFrame, figureA.9).

To the right of the figureA.9 appears inset image corresponding to selected characteristics, if loaded. Otherwise the label "Compressor data" allows to open by double click an image loading screen (class MapImage).

The data files and images of maps must be placed in the "maps" directory from which both classes work. Their names must be saved by the driver.

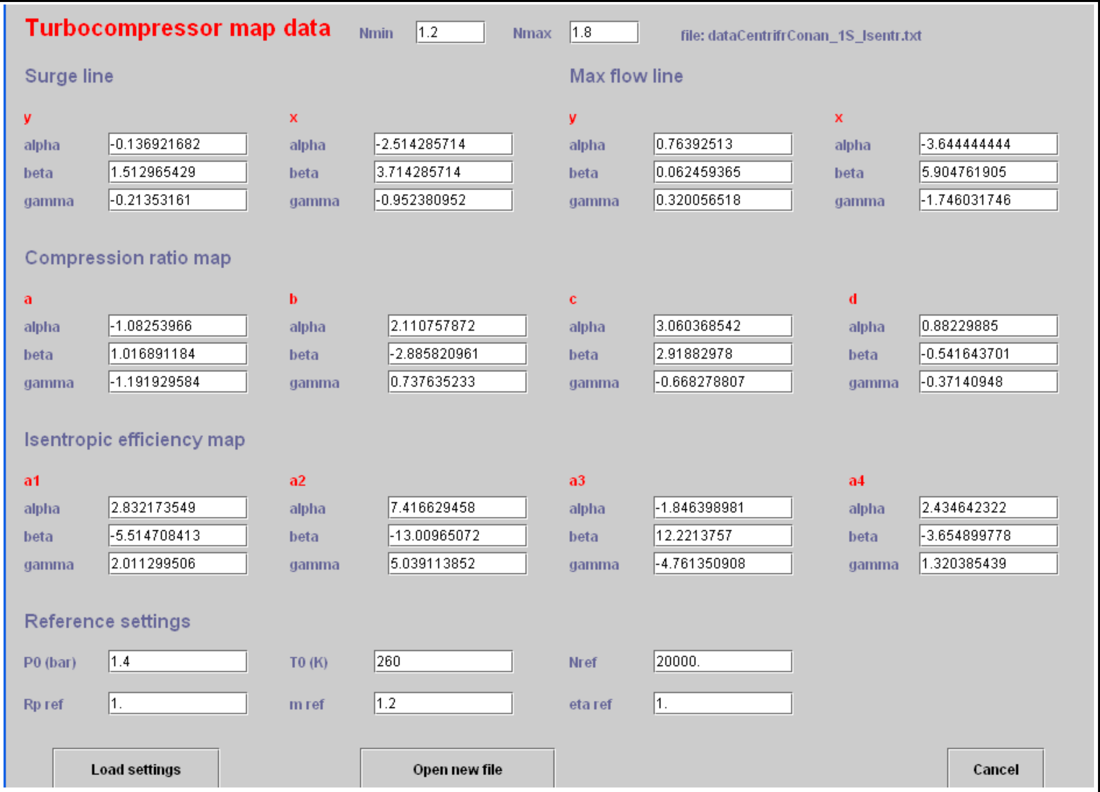
The mapping used here is expressed on a normalized flow. You must enter in the data file all reference values: P_0, T_0, N_{ref}, Rp_{ref}, m_{ref}, eta_{is_ref}, as well as the interval of variation of the reduced speed (here 1.2 to 1.8).

During design, we hold the nominal point of the mapping on that the compression process (later, we should be able to deduce the size, but this not yet implemented), which provides the compression rotation speed and values "eta design","Rp design"and"m design"displayed in the left of the screen, and potentially modifiable.

Above them appear dimensionless values needed to set the operating point on the mapping used. Their values are of course adjusted to the compressor inlet conditions.

Below these values is the field for defining the number of steps if you use a generic mapping (here 5).

The value of the rotation speed can be set from the driver screen if desired.



Turbocompressor map data Nmin 1.2 Nmax 1.8 file: dataCentrifrConan_1S_Isentr.txt

Surge line

	y		x
alpha	-0.136921682	alpha	-2.514285714
beta	1.512965429	beta	3.714285714
gamma	-0.21353161	gamma	-0.952380952

Max flow line

	y		x
alpha	0.76392513	alpha	-3.644444444
beta	0.062459365	beta	5.904761905
gamma	0.320056518	gamma	-1.746031746

Compression ratio map

	a		b		c		d
alpha	-1.08253966	alpha	2.110757872	alpha	3.060368542	alpha	0.88229885
beta	1.016891184	beta	-2.885820961	beta	2.91882978	beta	-0.541643701
gamma	-1.191929584	gamma	0.737635233	gamma	-0.668278807	gamma	-0.37140948

Isentropic efficiency map

	a1		a2		a3		a4
alpha	2.832173549	alpha	7.416629458	alpha	-1.846398981	alpha	2.434642322
beta	-5.514708413	beta	-13.00965072	beta	12.2213757	beta	-3.654899778
gamma	2.011299506	gamma	5.039113852	gamma	-4.761350908	gamma	1.320385439

Reference settings

P0 (bar)	1.4	T0 (K)	260	Nref	20000.
Rp ref	1.	m ref	1.2	eta ref	1.

Figure A.9 : Screen defining parameters of mapping of turbocompressor

Remarks on the refernce values of mapping files

The last lines of file mapping (bottom screen figures A.5 and A.9), provide the benchmarks that allow mapping to adapt to a given problem. The pressure and inlet temperature and speed of rotation generally correspond to those of the simulator for the nominal point. The ratio of compression / expansion and isentropic efficiency / polytropic should be equal to 1 if the mapping corresponds to the compressor used, but they can be modified if necessary. The value of the reference flow will typically close to the speed of compressor nominal point, since the maps were prepared for flow rates normalized.