



# GasTurb Details 6





# **GasTurb Details 6**

**An Utility for GasTurb**

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*by Joachim Kurzke*

## **GasTurb Details 6**

Joachim Kurzke is the principal author of GasTurb Details 6 and this manual. Additions have been made by the team of GasTurb GmbH.

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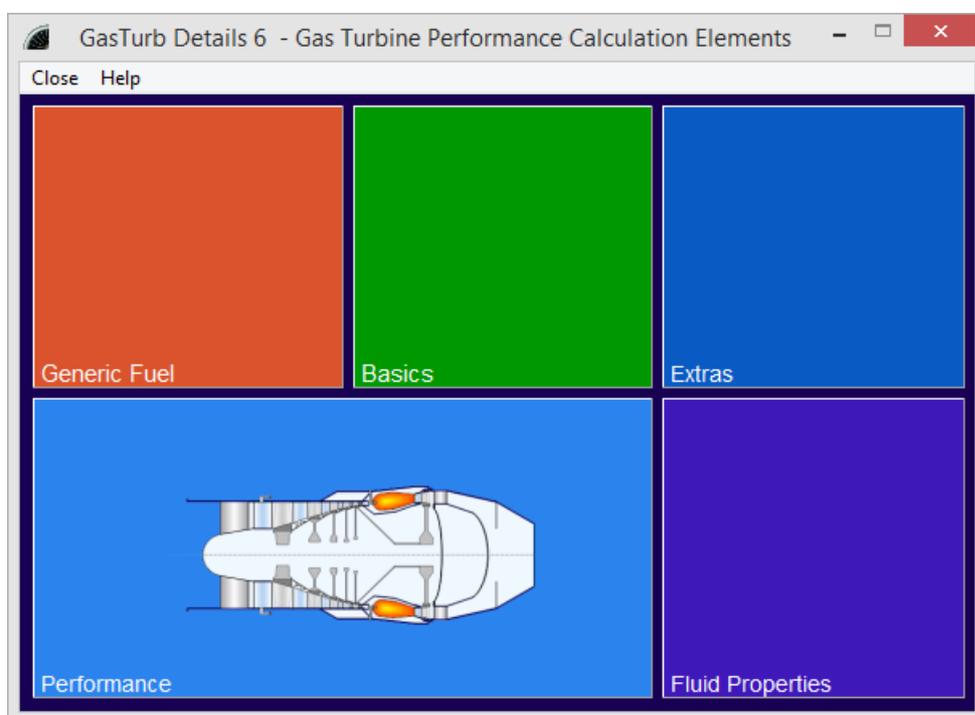
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# 1 Introduction

Understanding gas turbine performance is of importance for all concerned with gas turbine technology: the designers, the marketing staff, operators in the field and for maintenance people. The cycle program GasTurb makes the simulation of gas turbines for aircraft propulsion and for power generation easy.

GasTurb works with predefined engine configurations, thus allowing an immediate start of the calculation. One needs not to set up an engine configuration first, everything is ready to solve problems. Also many standard tasks are prepared in such a way that one gets answers very quickly. Due to the very practical graphical user interface even managers can use it. For more information about GasTurb have a look at the [website](#).

The program GasTurb Details 6 is an utility which allows to do some basic calculations with the same procedures as used in GasTurb. Thus, you can study details like compressors, turbines, mixers, nozzles etc. independently from GasTurb. The program is a sort of slide ruler specialized for gas turbine problems. The various calculation options are arranged on five panels. Click any panel and you will see what is on offer.



Two examples where you can benefit especially from GasTurb Details 6:

## Mixer

It is very difficult to isolate the effect of a [mixer](#) on the performance of a turbofan because you cannot use the same turbomachinery for both the unmixed and the mixed flow engines. With GasTurb Details 6 you can study the mixer alone and work out the thrust increase due to mixing.

## Convergent-Divergent Nozzle

The flow in a [convergent-divergent nozzle](#) is calculated from conservation of energy, mass, and momentum. The results of the simulation are displayed as numbers in a table, as well as in a graphical format which shows the static pressure along the nozzle.

### 1.1 What's New in GasTurb Details 6

Generally the quality of the graphical output has been enhanced significantly. Of course there are also new features in the program:

#### Temperature Units

In GasTurb Details 5 one could switch only between degrees Kelvin and Rankine. Now you can switch between degree Celsius and Fahrenheit in many places.

#### Shock Losses

The calculation of oblique shocks has been added to the group of basic correlations.

#### Pressure losses in a duct:

The Fanno and Rayleigh Lines are shown in the temperature-entropy diagram.

#### Atmosphere

How temperature, pressure, density and velocity of sound change in the atmosphere is presented graphically and as numbers. One can switch between ISA, Cold, Hot and a Tropical day. The altitude of some remarkable airports can be shown in the main atmosphere graphic.

#### Psychrometrics

The properties of humid air are relevant for determining the benefits of gas turbine inlet fogging, for example. A psychrometric chart and other figures describe the most important correlations. Additionally, one can get the properties of humid air also as numbers.

#### Steam Properties

The properties of steam as used in GasTurb for the combined cycle calculations are presented as numbers and as temperature-entropy and enthalpy-entropy diagrams.

Last but not least the bugs that were detected in the meantime have been removed. That does not mean that the software is now free of bugs - it is only free of known bugs. Should you detect an error in the program please give the publisher a message with a detailed description of the problem. If acknowledged as an error, the bug will be removed in due time and as a reward you will get a free update of the program.

### 1.2 Installation

#### Requirements

For running GasTurb Details 6, you need a PC with a color monitor which has a screen resolution of 1024x768 or better, running a Microsoft Windows operating systems (Windows 2000, Windows XP, Windows Vista, Windows 7 or 8). The license server, used for Floating and Site Licenses, can run on Windows, Max OS, Linux or Solaris.

## Installation

Run setup for installing the program. A wizard will lead you through the details of the installation.

Install GasTurb Details 6 in its own, new directory and do not install it in the directory of any previous program version you may have. Some of the files delivered with GasTurb Details 6 have the same file name as those of previous versions, but different file contents. Mixing the files from different versions of GasTurb Details might cause a program crash.

### Installation on a network

A Microsoft security patch now prevents HTML Help .CHM files from being opened on network drives. When you call help, "Action canceled!" will be displayed instead of the topic text. This will happen with all HTML Help files that you open over a network connection (note, that local HTML Help files will not be affected).

The reason for this error is a new and more strict security policy for Microsoft Internet Explorer. Microsoft is permanently updating MSIE to fix potential or real security threats. In case of this error, the Microsoft Security Bulletin MS05-026 disables HTML Help files opened from a network drive. Learn more about the security threat in the Microsoft Knowledgebase Article KB896358.

When you install the program on a network, please ensure that the help file (file extension .CHM) gets installed on the local C: drive (this is recommended by Microsoft). If this is not possible or not desirable, you can explicitly register individual help files and folders to allow viewing them over the network or edit the Windows registry to make the security settings less strict in general. Microsoft describes the necessary steps in detail in the Knowledgebase article KB 896054.

## 1.2.1 License software

Additionally to GasTurb Details 6, you have to install a license software called CodeMeter Control Center®. This will be done automatically, if you check the respective box during the setup of GasTurb Details 6.

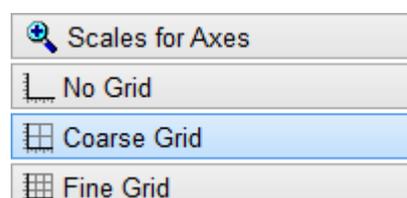
Moreover, in case you have a Floating or Site License, a license server has to be installed somewhere in your local network. Details about the installation of the license server and the activation of licenses can be found in a guide you have received together with your license information via email.

If you experience any kind of problems during the installation, please contact the support.

## 1.3 General Hints

### 1.3.1 Graphic

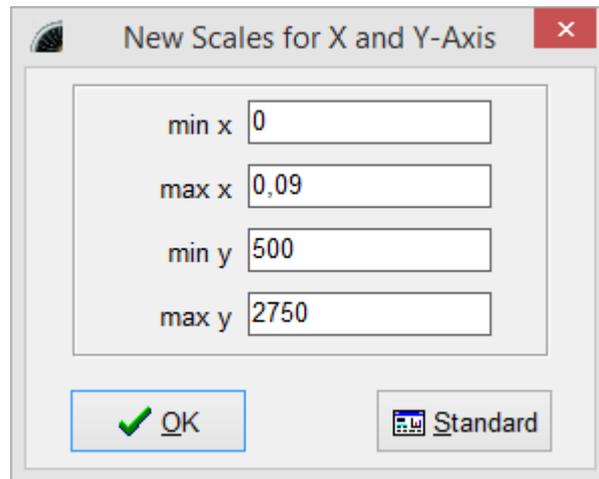
You can zoom into any calculated graph on the screen. Press the left mouse button and keep it down, move your mouse and release the mouse button when the rubber rectangle encloses the part of the graph you are interested in. Note that you can restore the original scales by clicking the right mouse button.



## General Hints

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After clicking the "Scales for Axes" button you can specify numbers for the axes of the graph. Please note that only appropriate numbers that yield nice numbers will be accepted by the program.



You can select all graphics with **No Grid**, **Coarse Grid** and **Fine Grid**.

### 1.3.2 Nomenclature

The nomenclature follows the International Standards as described in the SAE recommended practice document ARP 755C

A	Area
amb	Ambient
A8	Nozzle throat area
A9	Nozzle exit area of a convergent-divergent nozzle
eta	Efficiency
F	Thrust
far	Fuel-air-ratio
H	Enthalpy
H	Specific work
ISA	International Standard Atmosphere
Mn	Mach number
P	Total pressure
Ps	Static pressure
PW	Power
RNI	Reynolds number index
T	Total temperature
Ts	Static temperature
U	Circumferential velocity
V	velocity
Vax	Axial velocity
W	Mass flow
W	Relative velocity (in velocity triangles)

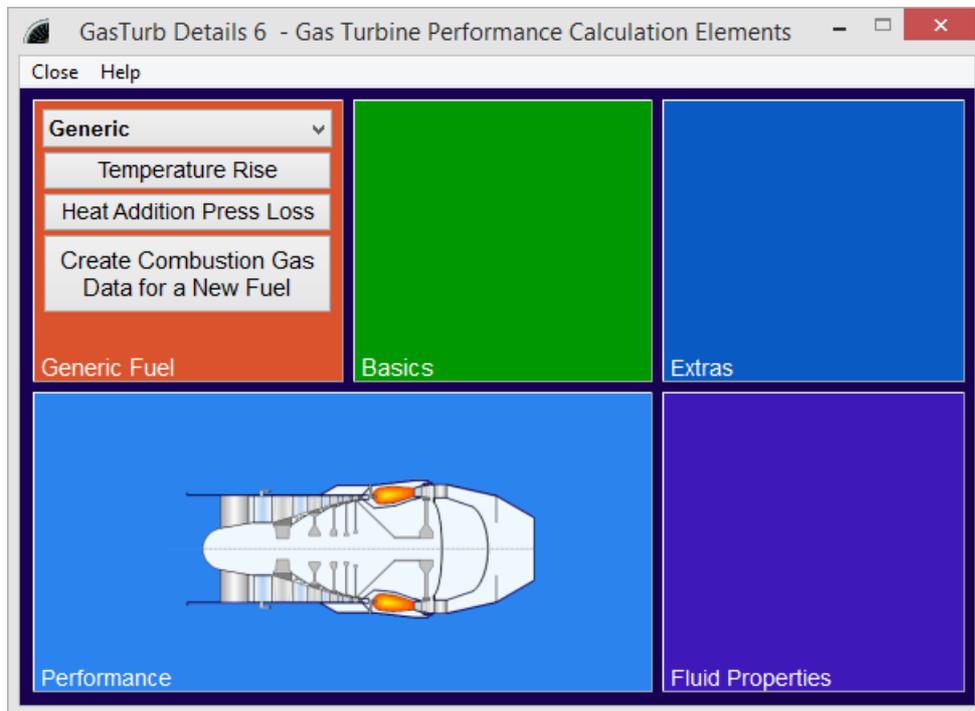
### 1.3.3 Units

You can switch between SI units and US customary units and in many places also select between Kelvin and Celsius respectively Rankine and Fahrenheit.

<input checked="" type="radio"/> Kelvin <input type="radio"/> Celsius	<input type="radio"/> Rankine <input checked="" type="radio"/> Fahrenheit
 Convert to US Units	 Convert to US Units
 Convert to SI Units	 Convert to SI Units

## 2 Fuel Panel

The top left panel deals with fuel and combustion topics. Select the fuel to be used everywhere in GasTurb Details 6 from the drop down list. The name of the selected fuel is shown as bottom line on the fuel panel. The **Temperature Rise** due to combustion can be studied as well as the **Heat Addition Pressure Loss**. If you are interested in a liquid or gaseous fuel with a special chemical composition then click the button **Create Combustion Gas Data for a New Fuel**.



### 2.1 Fuel Properties

In gas turbines hydrocarbons are often used as fuel. Hydrocarbons composed of 86.08% carbon and 13.92% hydrogen (by mass) burn with air such that the molecular weight, and therefore also the gas constant of the combustion products, is exactly that of dry air  $\{R=287.05 \text{ J}/(\text{kg K})\}$ . The lower heating value is 43.1 MJ/kg at  $T=288\text{K}$ . In GasTurb this type of fuel is called the **Generic fuel**. Kerosene, JP-4 and other fuels used in aviation and in gas turbines for power generation are composed of hydrocarbons in such a way that their properties come close to that of the generic fuel described above. JP-10 (chemical composition  $\text{C}_{10}\text{H}_{16}$ ) is a type of fuel which has more energy per volume and less energy per mass compared to the standard fuels used in aviation.

The chemical composition of natural gas can vary widely. For the calculation of the data used in GasTurb natural gas with 90% (by mass)  $\text{CH}_4$  and 10%  $\text{C}_2\text{H}_6$  is considered.

The type of fuel can be selected from the drop-down list in the top left panel of the main program window.

You can easily create additional gas property data sets for any hydrocarbon fuel by selecting the option [Create Combustion Gas Data for a New Fuel](#).

## 2.2 Temperature Rise

The gas properties of air and combustion products are stored in tables that are read when a type of fuel is selected. These tables are calculated with the NASA equilibrium code from Gordon McBride. They contain data for the isentropic exponent, specific heat, molecular weight, enthalpy and entropy as a function of temperature, fuel-air-ratio and water-air-ratio.

For the evaluation of the isentropic exponent, the specific heat etc. the only species considered are N<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O, CO<sub>2</sub> and Ar. This guarantees that the composition of the combustion products is independent of pressure. All calculations in GasTurb, except those for combustion, are done for constant gas compositions. Allowing combustion products like CO or NO<sub>x</sub> while generating the gas property tables would cause erroneous results in GasTurb.

The equilibrium temperature of the combustion process is stored as a function of fuel type, fuel-air-ratio, air temperature, pressure, humidity, water-fuel-ratio and steam-fuel-ratio. While calculating the equilibrium temperature there are no restrictions to the type of combustion products imposed, i.e. dissociation is taken into account.

The temperature of the fuel is 298.15K. The water temperature is the same while the steam temperature is assumed to be equal to the air temperature.

Inlet Temperature	T1	K	700	<input checked="" type="checkbox"/> input
Injected Fuel-Air-Ratio	FAR		0,03	<input checked="" type="checkbox"/> input
Exit Temperature	T2	K	1696,01	<input type="checkbox"/> input
Temperature Rise	T2 - T1	K	996,007	<input type="checkbox"/> input
Pressure	Ps	kPa	94,0446	input
Inlet Gaseous Water-Air-Ratio	WAR		0	input
Injected Water-Fuel-Ratio	WFR		0	input
Injected Steam-Fuel-Ratio	SFR		0	input
Steam Temperature	T steam	K	0	input
Fuel Heating Value	FHV	kJ/kg	43124	input
NO <sub>x</sub> Severity Index	sNO <sub>x</sub>		0,00932864	output
Effect of Dissoziation	delta T2	K	8,02111	output

For a single point calculation any reasonable combination of input quantities may be selected by marking the corresponding input check boxes.

## 2.3 Efficiency

Modern combustion chambers have very high efficiency at design conditions. At part load near idle and at very high altitude, however, the burner efficiency can deviate noticeable from 100%.

Burner efficiency can be correlated with burner loading which is defined as

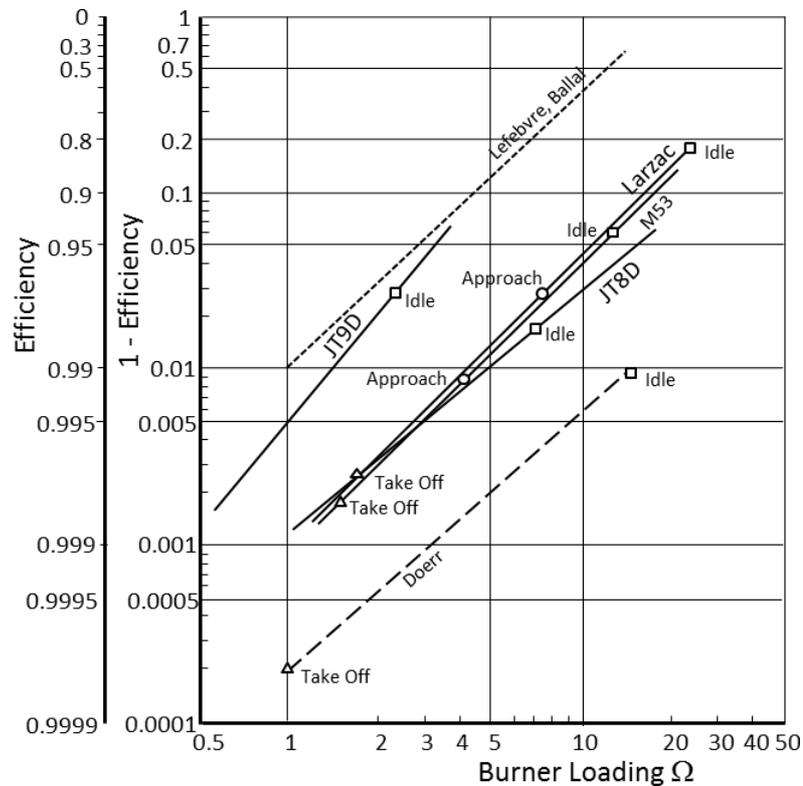
$$\Omega = \frac{W_{31}}{P_3^{1.8} \cdot e^{T_3/300K} \cdot Vol}$$

with

$W_{31}$	Air mass flow
$P_3$	Pressure [bar]
$T_3$	Inlet temperature [K]
Vol	Burner volume [m <sup>3</sup> ]

## Efficiency

For the cycle design point in GasTurb the burner efficiency is an input and the burner loading is by definition equal to 100%. For part load conditions the relative burner loading  $\Omega / \Omega_{des}$  can be determined without knowing the burner volume because the volume is invariant.



The figure above is taken from [Reference 10](#) and shows that the change in burner efficiency with load can be approximated by

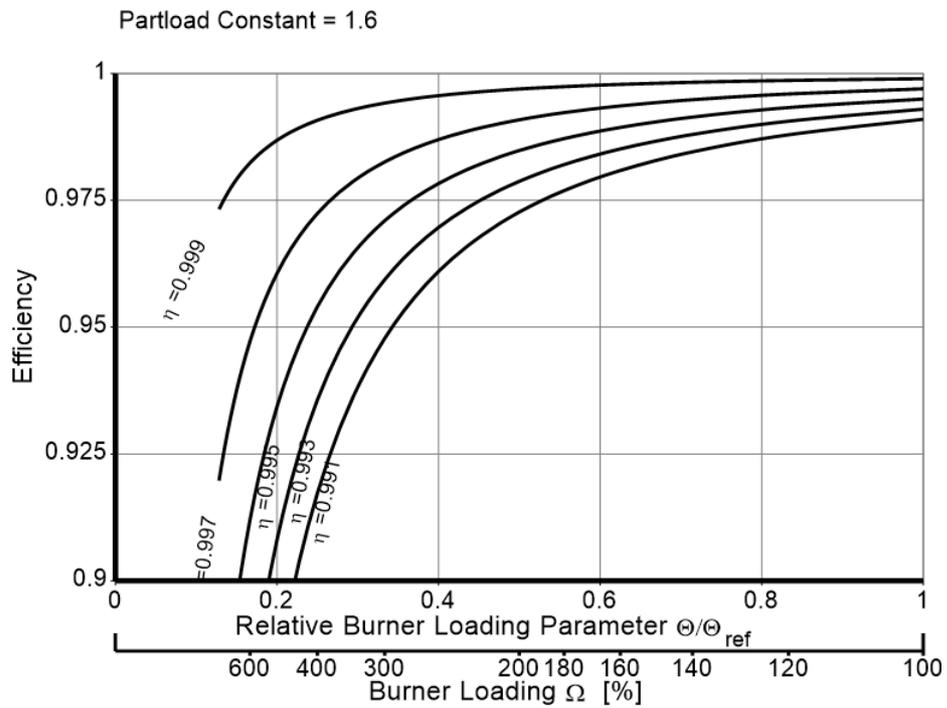
$$\log(1 - \eta) = a + b \cdot \log(\Omega / \Omega_{ds})$$

The constant  $a$  in this formula is correlated with the design point efficiency:

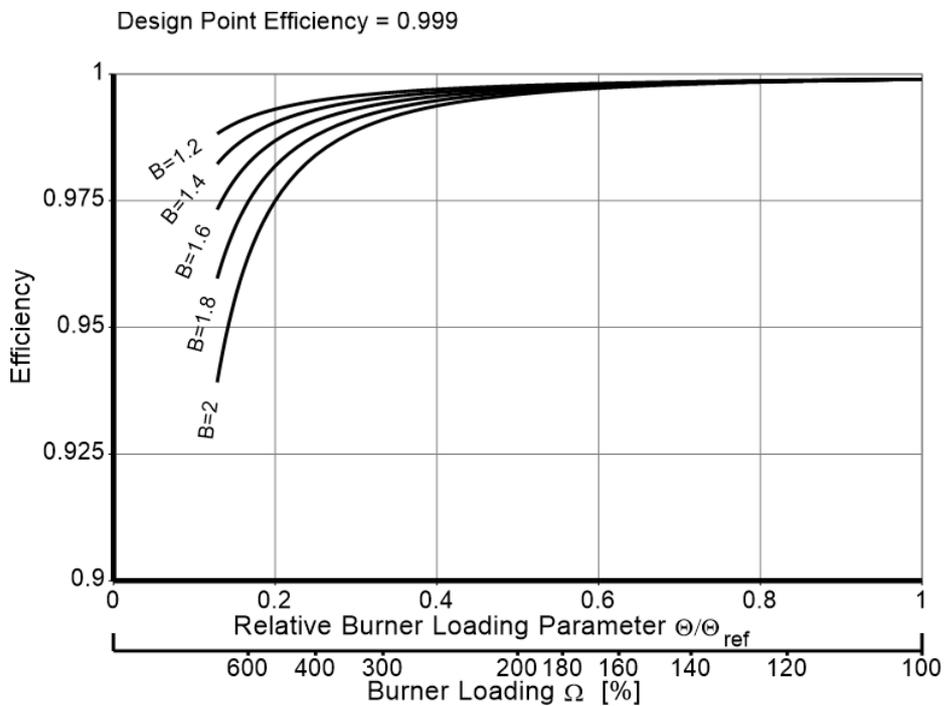
$$a = \log(1 - \eta_{ds})$$

Thus it is possible to describe the burner part load efficiency trend with a single property, the *burner part load constant*  $b$ .

Some authors use instead of burner loading the burner loading parameter which is the inverse of . In the next two figures there are scales for both and . The first figure shows off-design efficiencies with the burner part load constant of 1.6 (the GasTurb default value) in combination with various burner design point efficiencies.

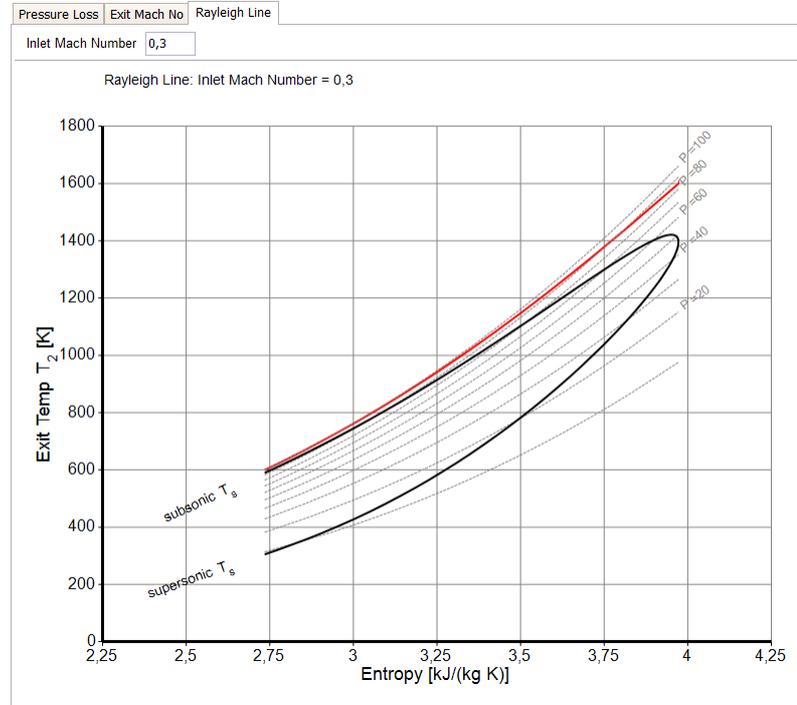


The effect of the part load constant on the burner efficiency is shown in the first figure below for an example with cycle design point efficiency of 0.999.

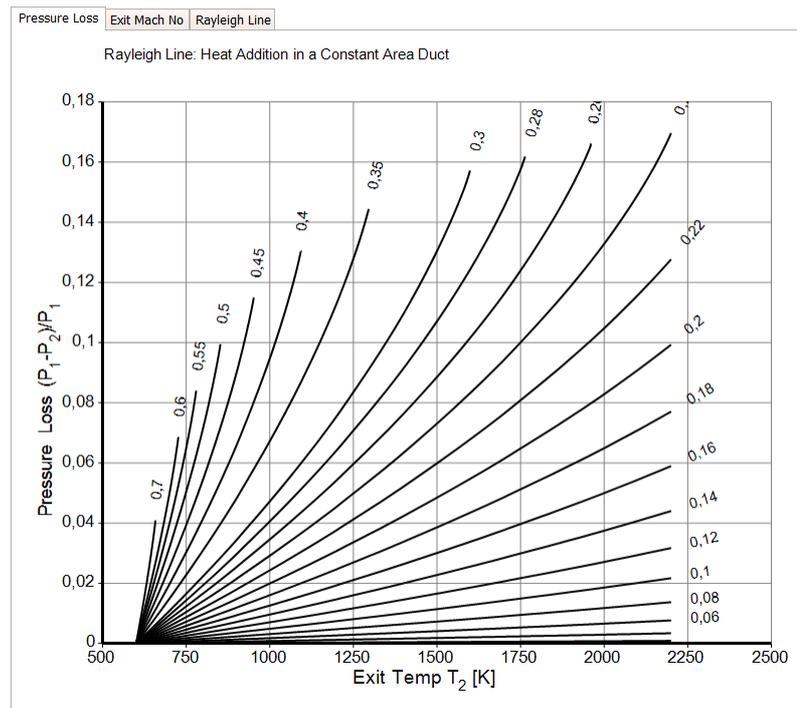


## 2.4 Heat Addition Pressure Loss

When heat is added in a frictionless duct with constant area the total pressure will drop. The duct exit number increases with duct inlet Mach number until the duct exit chokes. A series of heat addition points with duct exit Mach numbers from subsonic to supersonic Mach numbers plotted in a temperature-entropy diagram is called the **Rayleigh line**.



The total pressure loss due to heat addition is also called the **fundamental pressure loss**. This loss is considered in GasTurb only when reheat systems (afterburners, augmentors) are considered. The fundamental pressure loss is ignored with main combustors.



## 2.5 How to Create a New Fuel Data Set

### 2.5.1 Overview

The gas property data sets for GasTurb and GasTurb Details 6 are created with the NASA Computer program **CEA** (Chemical Equilibrium with Applications) which calculates chemical equilibrium compositions and properties of complex mixtures. CEA represents the latest in a number of computer programs that have been developed at the NASA Lewis (now Glenn) Research Center during the last 45 years. These programs have changed over the years to include additional techniques. The program is written in ANSI standard FORTRAN by Bonnie J. McBride and Sanford Gordon. It is in wide use by the aerodynamics and thermodynamics community, with over 2000 copies in distribution.

You can get the program together with a graphical user interface from the internet at <http://www.grc.nasa.gov/WWW/CEAWeb>. CEAgui is the Java Graphical Users Interface Application for the FCEA2.exe program. CEAgui allows the user to easily create or modify an input file, allows to run the program and view the output file. Note that CEAgui is not needed for creating a new fuel data set for GasTurb, the FCEA2.exe program is sufficient.

With GasTurb Details 6 you create two input data sets for the program FCEA2.exe, the first is for the temperature rise due to combustion and the second is for the gas properties of air and combustion gases. After running these two input data sets in the DOS window which opens when you run FCEA2.exe, GasTurb Details 6 will read the two files with the extension **plt** that are output of FCEA2.exe and combines them to a single file with the extension **prp**. Furthermore the new fuel name is added to the file **Fuels.gtb**.

These are the 9 steps to be followed:

1. Enter name of the new fuel
2. Enter the fuel composition
3. Enter the path to FCEA2.exe
4. Enter the path to GasTurb
5. Create CEA temp rise input
6. Run FCEA2 with that input
7. Create CEA gas prop input
8. Run FCEA2 with that input
9. Make GasTurb files

### 2.5.2 Naming the New Fuel

The gas property data set is identified in GasTurb and GasTurb Details by its name. The new name will be inserted into the file **Fuels.gtb** and it will also be employed as file name. If you name the fuel **My New Fuel**, then a line with My New Fuel will be added to the file Fuels.gtb and the final gas property file will get the name MyNewFuel.prp.

The input and the output of the FCEA2.exe program will also employ the fuel name. The first input file (which creates the temperature rise information) will be named **MyNewFuel\_DT.inp** and the second input file (which is for the gas properties) gets the name **MyNewFuel\_GP.inp**. The corresponding FCEA2.exe output files get automatically the same file names but with different extensions. The following four files will be created:

- **MyNewFuel\_DT.out**
- **MyNewFuel\_DT.plt**
- **MyNewFuel\_GP.out**
- **MyNewFuel\_GP.plt**

Only the two files with the extension .plt will be used for creating the final MyNewFuel.prp file. The other two files are for checking the CEA program output in detail. Check especially if at the end of the files with the extension .out there is an error message. An error reported by CEA makes the generated files unusable with GasTurb and GasTurb Details.

### 2.5.3 Fuel Composition

The most simple way of defining a fuel composition is to select the reactants from the file **thermo.inp** which is part of the FORTRAN source code package offered on the NASA website. You should copy the most recent version of thermo.inp to the GasTurb Details 6 program directory before creating a data set for a new fuel. Note that GasTurb Details 6 offers only those reactants from thermo.inp that are relevant for gas turbine applications.

When defining the fuel composition you can enter either mass fractions or mole fractions. If there are several reactants then the sum of the mass fractions and the sum of the mole fractions must be equal to 1.

If you consider a reactant which is not part of thermo.inp then you have to provide a reactant name **which is not found in thermo.inp**, the formula and an assigned enthalpy (heat of formation) in kJ/kg mol. In the formula only reactants composed of C, H, O, N and S are allowed. If the reactant name is found in thermo.lib then your input in GasTurb Details 6 will be ignored and the formula as well as the assigned enthalpy will be taken from thermo.inp.

An approximate value for the heat of formation  $dH_f$  (assigned enthalpy) of a hydrocarbon with the formula  $CH_y$  ( $y=H/C$  atom ratio) can be found from the following relationship which is taken from Reference 5:

$$\Delta H_f = 35.5038 - 29.8646 \cdot y + 0.013 \cdot y^2$$

### 2.5.4 Path to CEA and GasTurb

For storing the input files for FCEA2.exe and for reading the output created by this code GasTurb Details 6 needs to know the path to the directory where FCEA2.exe resides on your computer.

The final new gas property data sets created in the last step will be stored in the directory which you specify for GasTurb. That can be either the directory where GasTurb Details 6 resides or the directory of GasTurb.

### 2.5.5 Create CEA Temperature Rise Input

When the fuel composition is defined, then the first input file for the FCEA2.exe program can be created, it will be named **MyNewFuel\_DT.inp**. In GasTurb Details 6 click the corresponding button or select the menu option for that. The file will be created in the directory which you have specified as path to FCEA2.exe.

This input to FCEA2.exe will create results with the equilibrium burner exit temperature as a function of inlet air temperature, injected fuel-air-ratio and pressure. No reaction product is excluded from the calculation of the chemical equilibrium and thus dissociation is taken into account. Besides dry air also air with medium and high humidity is considered. Moreover, fuel with water respectively steam content is taken into account. If the default value of zero for the steam temperature is input then the steam temperature will be set to the same values as the air temperature.

Topic	Quantity	Symbol in table	Default
Medium humidity	water-air-ratio	war1	0.03
High humidity	water-air-ratio	war2	0.10
Water injection	water-fuel-ratio	wqf	1
Steam injection	steam-fuel-ratio	sqf	1
Fuel temperature		Tf	298.15K
Water temperature		Tw	298.15K
Steam temperature		Ts	0

In previous versions of GasTurb Details (compiled before July 2009) the default values were hard coded in the program and could not be altered. If a newly created gas property data set must be consistent with the standard gas property files delivered together with GasTurb Details 6 respectively GasTurb then use the default values. Note that the enhanced version of the gas property file contains additional data for the case with both water and steam injection into the burner.

### 2.5.6 First Run of CEA

Go to the directory where FCEA2.exe resides on your computer and execute this program. Do not use the graphical user interface CEAgui. A DOS box will open and wait for your input: type MyNewFuel\_DT (replace MyNewFuel by the your actual fuel name, see section about [naming the new fuel](#)) and then hit the enter key to start the FCEA2.exe program. The two files MyNewFuel\_DT.out and MyNewFuel\_DT.plt will be created in the directory in which FCEA2.exe resides. Have at least a short look at the file MyNewFuel\_DT.out (use your favorite ASCII editor for that) and check for error messages at the end of the file before proceeding with GasTurb Details 6.

### 2.5.7 Create CEA Gas Property Input

When the chemical equilibrium temperature information has been created, then the second input file for the FCEA2.exe program can be prepared. The gas property tables contain data for dry and wet air as well as combustion products for a single high fuel-air-ratio. This fuel air ratio must be lower than the stoichiometric fuel-air-ratio of the fuel considered. To make sure that this condition is fulfilled, GasTurb Details 6 reads the temperature rise output file from the FCEA2 program and sets the fuel-air-ratio in the gas property input file to a suitable number, lower than the stoichiometric value.

Click the corresponding button or select the menu option for reading the temperature rise table and then creating the gas property input file MyNewFuel\_GP.inp. This file will be stored in the directory which you have specified as [path to CEA](#).

For power generation gas turbines the burner exit temperature range is typically between 1200 K and 1600 K at base load operation. For normal hydrocarbon fuels this means that the fuel-air-ratio range is typically 0.017 ... 0.021. In gas turbines employed for aircraft propulsion the temperatures are higher, but even in afterburners the fuel-air-ratios do not exceed 0.06. Therefore the standard fuel-air-ratio range in the gas property tables for GasTurb cover only the fuel-air-ratio range from 0 to 0.08.

## How to Create a New Fuel Data Set

However, when Syngases (non-hydrocarbon fuels with molar composition:  $1/3 \text{ CO} + 1/3 \text{ H}_2 + 1/3 \text{ CO}_2$ , for example) are burnt in industrial gas turbines, the typical fuel-air-ratios are approximately 10 times higher, between 0.17 and 0.21. Therefore the range of the fuel-air-ratio in the gas property tables needs to be extended over the normal range (0 ... 0.08) to 0 ... 0.16 or higher.

If you are creating a gas property data set for a low caloric fuel then it can happen that you need to re-run the temperature increase file with a higher fuel-air-ratio range before you can create the gas property input file. It might also happen that the CEA program stops with an error message before all cases have been calculated. In this case try with a modified (lower) fuel-air-ratio until the CEA program finishes without an error message.

You can see the calculated fuel-air-ratio value that will be used for the generation of the gas property data on the last line on tabbed pages that are the lower right corner of your screen:

Dry Air	war=0,03	war=0,1	Molecular Weight	
	Moles/Moles Air	% Mass	% Mass	
N2	0,78084	0,755184	0,755184	
O2	0,209476	0,231416	0,231416	
Ar	0,009365	0,012916	0,012916	
CO2	0,000319	0,000485	0,000485	
H2O	0	0	0	
Fuel	0	0	0	
Fuel-air-ratio	in gas property	tables =		

This input to FCEA2.exe will create tables with isentropic exponent, specific heat, molecular weight, enthalpy and entropy as function of temperature, fuel-air ratio and three levels of humidity in terms of water-air-ratio ( $\text{war}=0$ ,  $\text{war}=\text{war1}$  and  $\text{war}=\text{war2}$ ). In this calculation - which is performed at the constant pressure of 100 bar - only the reaction products Ar, CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, O<sub>2</sub> and SO<sub>2</sub> are permitted. Thus dissociation is not considered, the molecular weight is independent from temperature and pressure. The gas properties are a function of temperature, humidity and fuel-air-ratio only.

### 2.5.8 Second Run of CEA

Go again to the directory where FCEA2.exe resides on your computer and execute this program. Do not use the CEA graphical user interface. A DOS box will open and wait for your input: type **MyNewFuel\_GP** (replace MyNewFuel by the your actual fuel name, see section about [naming the new fuel](#)) and then hit the enter key to run FCEA2.exe. The two files MyNewFuel\_GP.out and MyNewFuel\_GP.plt will be created in the directory in which FCEA2.exe resides. Have at least a short look at the file MyNewFuel\_GP.out and check for error messages before proceeding with the final step in GasTurb Details 6.

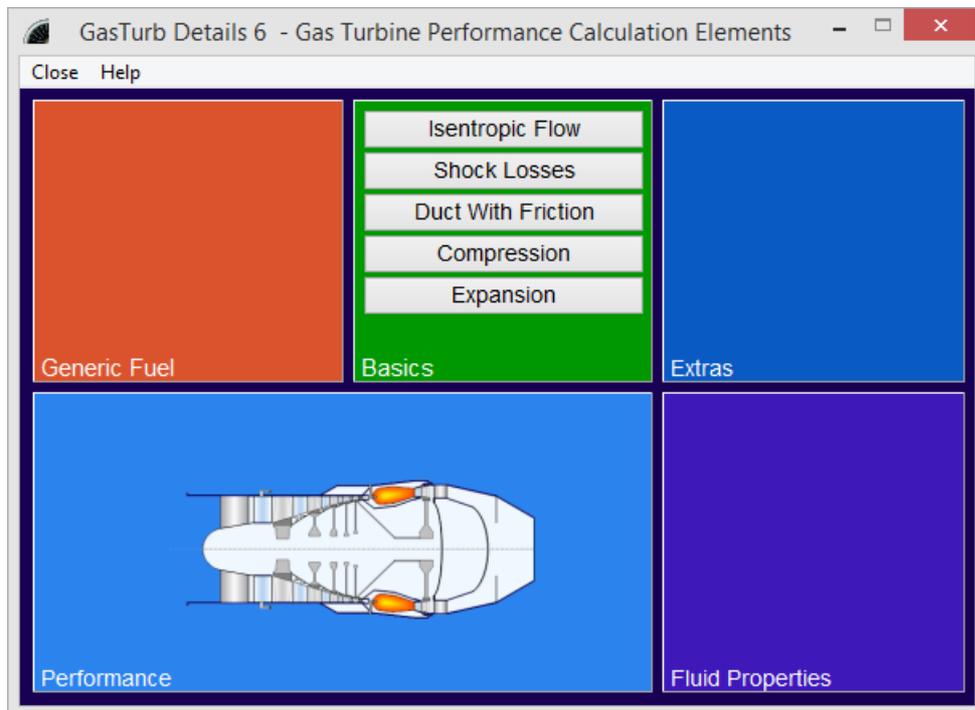
### 2.5.9 Make GasTurb Files

After running the two input data sets with FCEA2.exe, GasTurb Details 6 will read the two files **MyNewFuel\_DT.plt** and **MyNewFuel\_GP.plt** and combines them to the single file **MyNewFuel.prp**. Furthermore the new fuel name My New Fuel is added to the file **Fuels.gtb**. These two new files are stored in the directory which you have specified for GasTurb Details 6 respectively GasTurb. The files that have been there before will be overwritten without warning.

If you want to remove the data of a fuel composition (for example MyNewFuel) then open the file Fuels.gtb in any ASCII editor, delete the corresponding line and delete also the file MyNewFuel.prp.

### 3 Basic Panel

The top middle panel deals with basic thermodynamic and gasdynamic correlations. A click on a topic button opens the relevant window.



#### 3.1 Isentropic Flow

The table contains the most important relationships for isentropic flow. Any reasonable combination of input quantities may be selected by checking the corresponding boxes. All calculations are done employing the [entropy function](#).

Fuel-Air-Ratio	FAR		0	<input checked="" type="checkbox"/> input
Water-Air-Ratio	WAR		0	<input checked="" type="checkbox"/> input
Total Temperature	T	K	1000	<input checked="" type="checkbox"/> input
Total Pressure	P	kPa	500	<input checked="" type="checkbox"/> input
Mach Number	M		1	<input checked="" type="checkbox"/> input
Velocity	V	m/s	574,688	<input type="checkbox"/> input
Static Temperature	Ts	K	853,142	<input type="checkbox"/> input
Static Pressure	Ps	kPa	268,497	<input type="checkbox"/> input
Total/Static Press Ratio	P/Ps		1,86222	<input type="checkbox"/> input
Total/Static Temp Ratio	T/Ts		1,17214	<input type="checkbox"/> input
Critical Area Ratio	A/Acrit		1	<input type="checkbox"/> input
Mass Flow	W	kg/s	1	<input checked="" type="checkbox"/> input
Area	A	m <sup>2</sup>	0,00158711	<input type="checkbox"/> input
Corrected Flow	$W \cdot \sqrt{T}/P$	kg <sup>*</sup> sqrt(K)/(s <sup>*</sup> kPa)	0,0632456	<input type="checkbox"/> input
Corrected Flow/Area	$W \cdot \sqrt{T}/(P \cdot A)$	kg <sup>*</sup> sqrt(K)/(s <sup>*</sup> kPa <sup>*</sup> m <sup>2</sup> )	39,8495	<input type="checkbox"/> input

The reference point in the graphs of the [Total-Static Relations](#) corresponds to the single point data that you have calculated before selecting a graphical output. The data of the reference point will define the range of the data in the [graphs](#).

### 3.1.1 Total Temperature

For a thermodynamic cycle calculation the true (static) temperature is normally of no relevance. What matters is the total or stagnation temperature.

The stagnation temperature is the temperature which the gas would possess when brought to rest adiabatically. The symbol for total temperatures is  $T$ . Static temperatures are marked as  $T_s$ . The symbol for ambient temperature is  $T_{amb}$ .

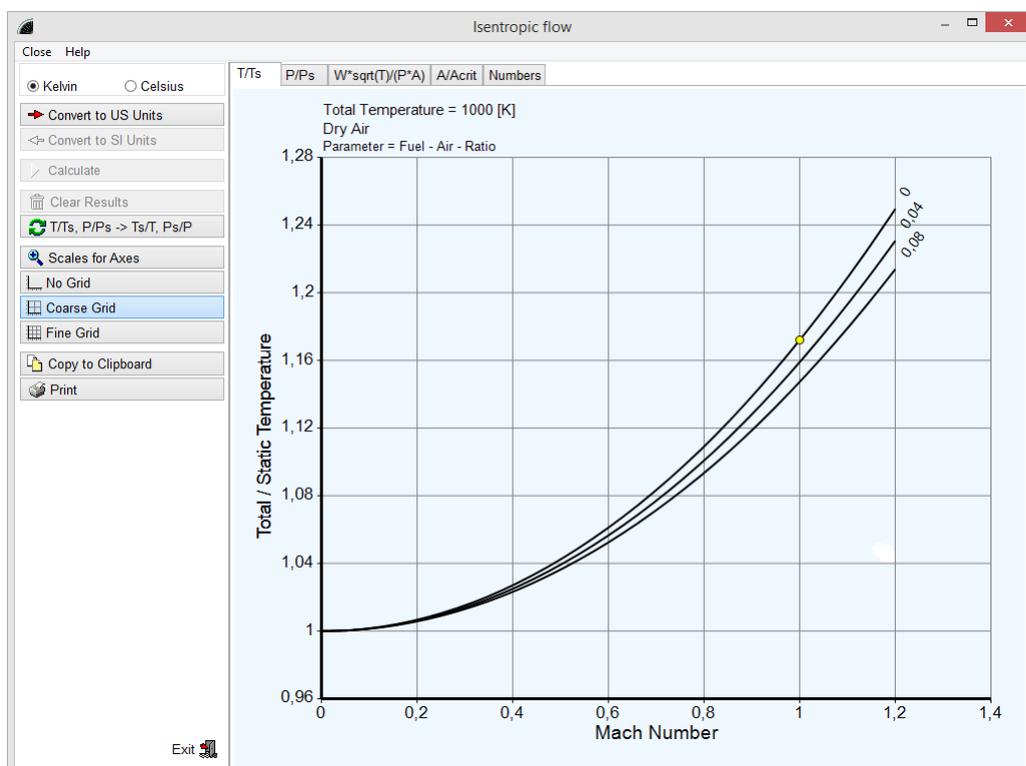
### 3.1.2 Total Pressure

For a thermodynamic cycle calculation the true (static) pressure is of relevance mostly for the intake and the nozzle. What matters for most components and gas turbine performance calculations in general is the total or stagnation pressure.

The stagnation pressure is the pressure which the gas would possess when brought to rest adiabatically. The symbol for total pressures is  $P$ . Static pressures are marked as  $P_s$ . The symbol for ambient pressure is  $P_{amb}$ .

### 3.1.3 Total - Static Relations

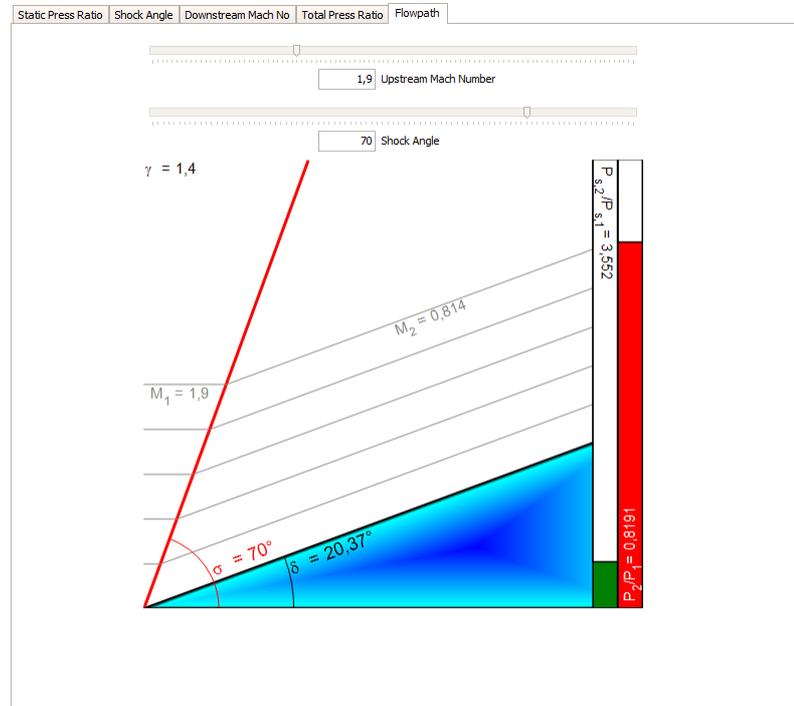
In this window you can study the correlations between total and static pressures and temperatures graphically. All calculations are done with the help of the [entropy function](#).



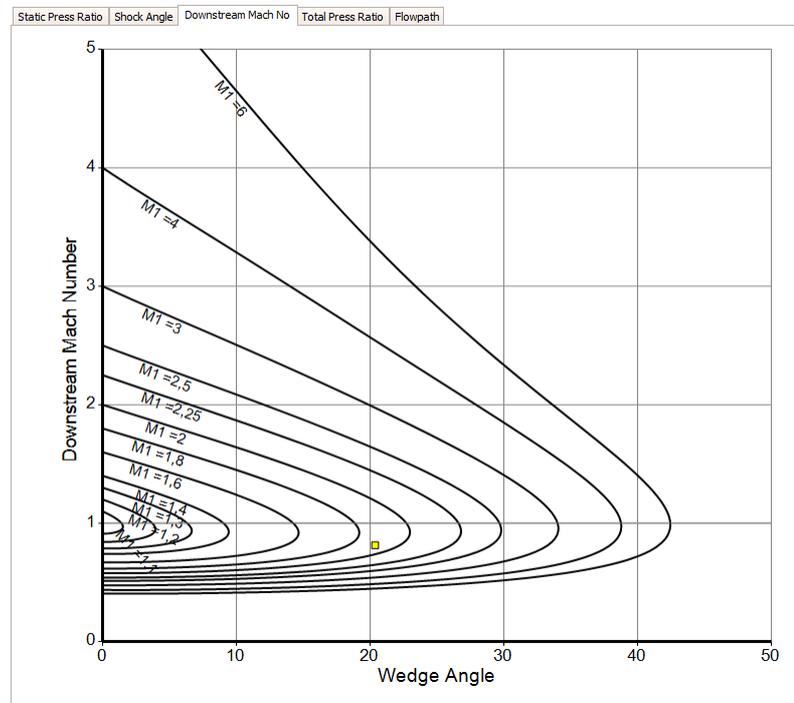
Before plotting the correlations you must calculate a single point. Specify as input any reasonable combination of parameters. After the calculation of this single point you can select any of the pictures. The single point defined before will define the Mach number range in the plot.

### 3.2 Shock Losses

Shock losses are of interest for supersonic aircraft intakes, for example. In an interactive picture you can play with upstream Mach Number and Shock Angle. The static pressure ratio  $P_{s2}/P_{s1}$  and the total pressure ratio  $P_2/P_1$  are shown as bars on the right side of the picture:



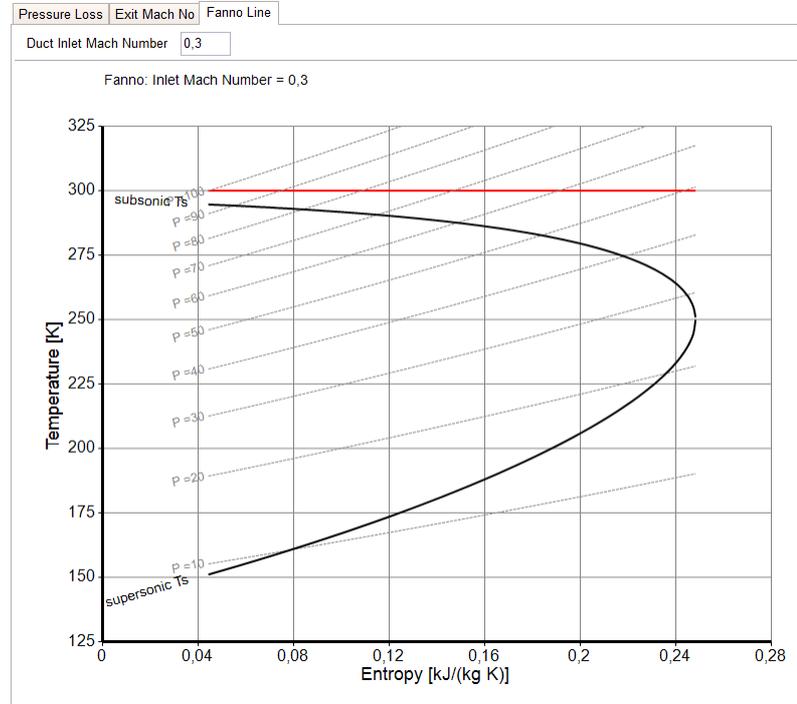
The data from the interactive graphic are shown as yellow rectangle in the other plots on offer:



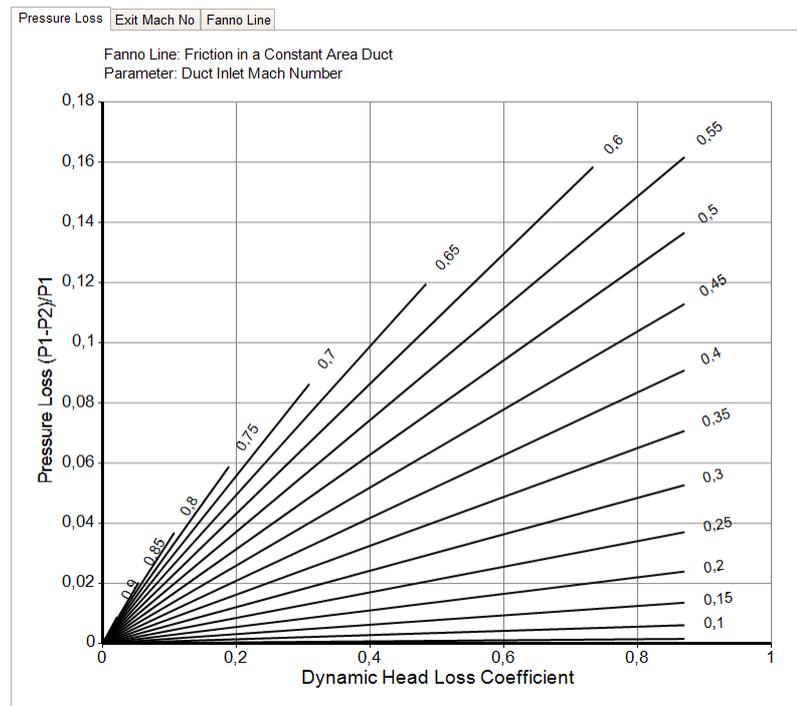
Note that all calculations are done employing a constant isentropic coefficient.

### 3.3 Duct With Friction

In a constant area duct with friction the exit Mach number increases with duct inlet Mach number until the duct exit chokes. A series of friction pressure loss points with duct exit Mach numbers from subsonic to supersonic plotted in the temperature-entropy diagram is called the **Fanno** line.



The total pressure loss in a constant area duct with friction depends on the inlet Mach number and the dynamic head loss coefficient  $c_{ld}$ . The duct total pressure at the duct exit is calculated as  $P_2 = P_1 \cdot c_{ld} \cdot (P_1 - P_{s1})$



### 3.4 Compression

#### 3.4.1 Compression Calculation

In the compression calculation window you can view the following correlations as graphics:

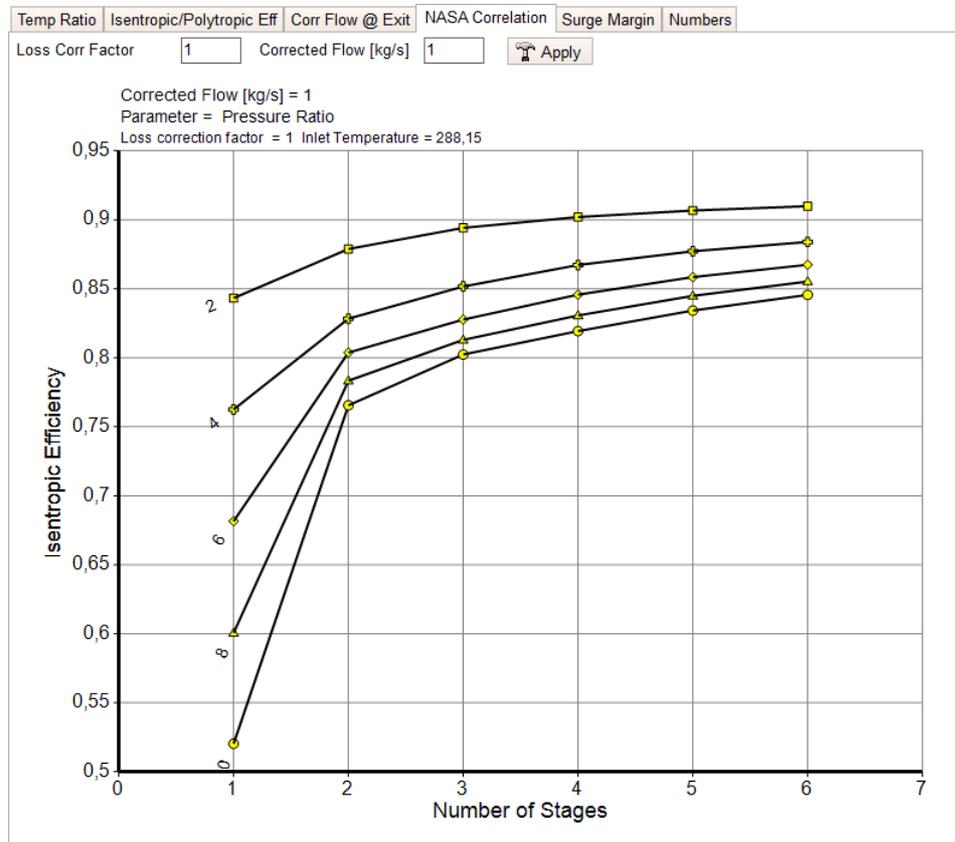
Temp Ratio | Isentropic/Polytropic Eff | Corr Flow @ Exit | **NASA Correlation** | Surge Margin

For single point calculations a table is offered in which you can enter your input data in many combinations. All calculations are done employing the [entropy function](#).

Water-Air-Ratio	WAR		0	Input
Inlet Temperature	T1	K	288,15	<input checked="" type="checkbox"/> input
Inlet Pressure	P1	kPa	101,325	<input checked="" type="checkbox"/> input
Isentropic Efficiency	eta,is		0,9	<input checked="" type="checkbox"/> input
Polytropic Efficiency	eta,pol		0,9261122	<input type="checkbox"/> input
Pressure Ratio	PqP		10	<input checked="" type="checkbox"/> input
Exit Temperature	T2	K	580,6661	<input type="checkbox"/> input
Exit Pressure	P2	kPa	1013,25	<input type="checkbox"/> input
Specific Work	dH	J/kg	298719,9	<input type="checkbox"/> input
Mass Flow	W	kg/s	1	<input checked="" type="checkbox"/> input
Power	PW	kW	298,7199	<input type="checkbox"/> input

#### 3.4.2 NASA Efficiency Correlation

NASA has published an efficiency correlation for axial flow compressors in [Reference 3](#).



Efficiency is in this correlation a function of stage loading and inlet corrected flow. The loss level in the original publication is for an advanced technology compressor. In GasTurb you can adjusted the efficiency result with a loss correction factor.

### 3.4.3 Exit Corrected Flow

The exit corrected flow is the corrected flow at the exit of a compressor or turbine:

$$W_{exit,corr} = W_{inlet,corr} \cdot \frac{\sqrt{T_{exit}/T_{inlet}}}{P_{exit}/P_{inlet}}$$

## 3.5 Expansion

Besides a single point calculation the following graphs are offered:

Temp Ratio	Ientropic/Polytropic Eff	Corr Flow @ Exit
------------	--------------------------	------------------

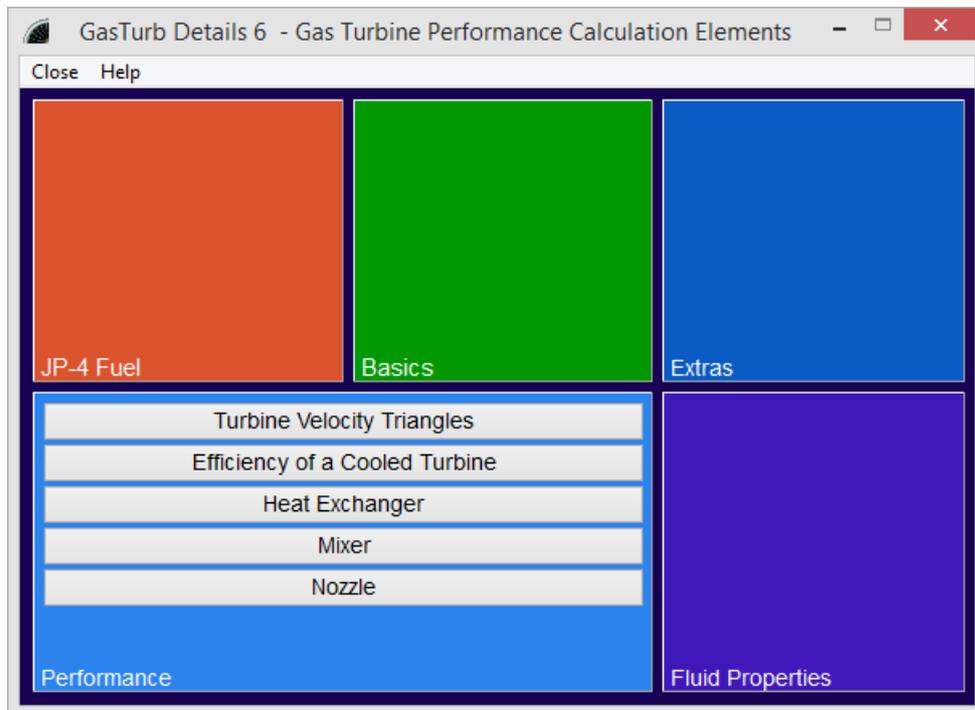
For a single point calculation any reasonable combination of input quantities may be selected by marking the corresponding input check boxes in the table:

Fuel-Air-Ratio	FAR		0	Input
Water-Air-Ratio	WAR		0	Input
Inlet Temperature	T1	K	288,15	<input checked="" type="checkbox"/> input
InletPressure	P1	kPa	101,325	<input checked="" type="checkbox"/> input
Ientropic Efficiency	eta,is		0,9	<input checked="" type="checkbox"/> input
Polytropic Efficiency	eta,pol		0,864675	<input type="checkbox"/> input
Pressure Ratio	PqP		10	<input checked="" type="checkbox"/> input
Exit Temperature	T2	K	163,0151	<input type="checkbox"/> input
ExitPressure	P2	kPa	10,1325	<input type="checkbox"/> input
Specific Work	dH	J/kg	125539,6	<input type="checkbox"/> input
Mass Flow	W	kg/s	1	<input checked="" type="checkbox"/> input
Power	PW	kW	125,5396	<input type="checkbox"/> input

All calculations are done employing the [entropy function](#).

## 4 Performance Panel

The panel on the lower left side gives access to some special component simulation procedures. The **Turbine Velocity Triangle** analysis deals with uncooled turbines. After a click on **Efficiency of a Cooled Turbine** a window opens in which various methodologies for the simulation of cooled turbines are compared. The **Heat Exchanger** calculations are very simple while the **Mixer** simulation is a more challenging problem. The **Nozzle** section covers both convergent and convergent divergent designs.



### 4.1 Turbine Velocity Triangles

The turbine design procedure does turbine geometry and efficiency calculations on a mean section basis for an axial flow turbine assuming symmetrical velocity diagrams for each stage (except the first stage, which has axial inlet flow). The method is a simplified version of the program published by NASA as [Reference 4](#).

## Turbine Velocity Triangles

Inlet Temperature		1500
Fuel-Air-Ratio		0,02
Inlet Pressure	kPa	2000000
Mass Flow	kg/s	70
Revolutions per Minute		18000
Power required	kW	35000
P_inlet/Ps_exit		0
Number of Stages		2
With Exit Guide Vanes [0/1]		0
Mean Inlet Diameter	m	0,6
Mean Exit Diameter	m	0,65
Inlet Radius Ratio		0,85
Exit Radius Ratio		0,75
V <sub>ax,exit</sub> / V <sub>ax,average</sub>		1
Loss Factor [0.3...0.4]		0,4
1. Rotor Tip Clearance	mm	0
% Eff. change for % Clear.		2

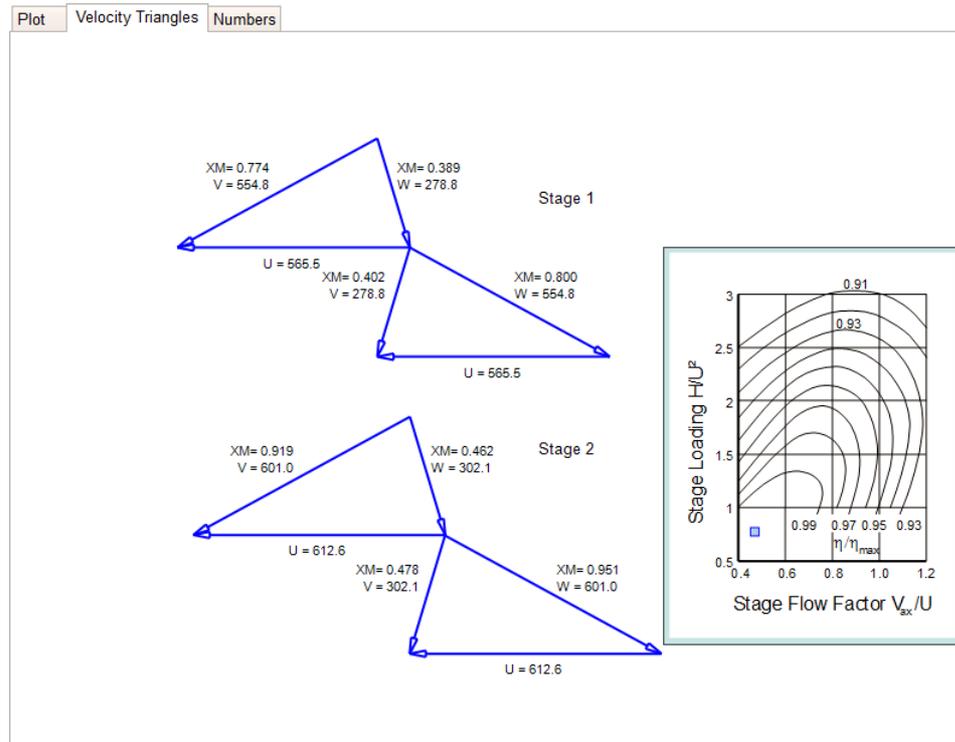
The efficiency calculated can be adjusted to any technology level by adapting the **Loss Factor**. The NASA report proposes to use for this factor a number in the range of 0.35 to 0.40. Large uncooled turbines of modern engines can be better described with values as low as 0.30.

The result for the above input data is:

Calculated Power	kW	35000
First Rotor rel Inl Temp	K	1406,206
Last Rotor abs Inl Temp	K	1312,413
Last Rotor rel Inl Temp	K	1202,335
First Stage Exit Radius Ratio		0,9025887
Last Stage Exit Radius Ratio		0,75
Exit Mach Number		0,4803627
Exit Angle	deg	16,53432
Stator Exit Angle	deg	61,19636
First Rotor Tip Clear.[%]		0
Total Efficiency (isentropic)		0,919669
Static Efficiency (isentropic)		0,8506204
First Stage H/T	J/(kg*K)	166,6667
First Stage H/u <sup>2</sup>		0,7817993
First Stage V <sub>ax</sub> /u		0,4726829
Last Stage Tip Speed	m/s	700,1264
Exit A*N <sup>2</sup>	m <sup>2</sup> *RPM <sup>2</sup> *E-6	61,43609

Flow angles are measured against the turbine axis. Positive angles are in direction of rotation.

The corresponding velocity triangles are shown as a graphic:



### 4.1.1 Efficiency

The total efficiency relates the work output of a turbine to the ideal work calculated from the total pressure at the turbine inlet to the total pressure at the turbine exit. This efficiency definition is appropriate if the kinetic energy at the turbine exit is not a loss for the process.

The isentropic efficiency of an un-cooled turbine is defined as

$$\eta_{is} = \frac{\Delta H}{\Delta H_{is}} = \frac{\frac{\gamma}{\gamma-1} \cdot R \cdot (T_1 - T_2)}{\frac{\gamma}{\gamma-1} \cdot R \cdot T_1 \cdot \left(1 - (P_2/P_1)^{\frac{\gamma-1}{\gamma}}\right)}$$

In this equation the isentropic exponent of the gas is a mean value between the inlet and the exit of the turbine. In GasTurb instead of a mean isentropic exponent the **entropy function** is used for correlating pressure ratio with isentropic specific work. This allows for the exact consideration of the temperature dependent variable isentropic exponent.

The total to static efficiency relates the work output of a turbine to the ideal work calculated from the total pressure at the turbine inlet to the static pressure at the turbine exit. This efficiency definition is appropriate if the kinetic energy at the turbine exit is a loss for the process. Otherwise the total efficiency definition is to be preferred.

## 4.2 Cooled Turbine

### 4.2.1 Introduction to Cooled Turbines

Quoting numbers for the efficiency of a turbine is ambiguous if the efficiency definition is not clearly defined. This is especially true for a heavily cooled turbine where for the same machine the efficiency may be quoted as 88% or 91%, for example. In aero-engine industry, several different turbine efficiency bookkeeping systems are in use. Since nearly always a consortium of two or more companies is involved into any new engine project it is important to understand the various bookkeeping systems.

There are two basically different methodologies for defining the efficiency of a cooled turbine: One can deal with the turbine as a sort of "black box" or go into the details of the expansion process.

A discussion about the merits of the different efficiency definitions can be found in [Reference 2](#).

In GasTurb cooled multistage turbines are simulated as [equivalent single stage turbines](#). In the chapter "Calculation Options" it is described how to derive input data for the methodology employed by GasTurb from numbers for other efficiency definitions and for more complex secondary air systems than simulated in GasTurb.

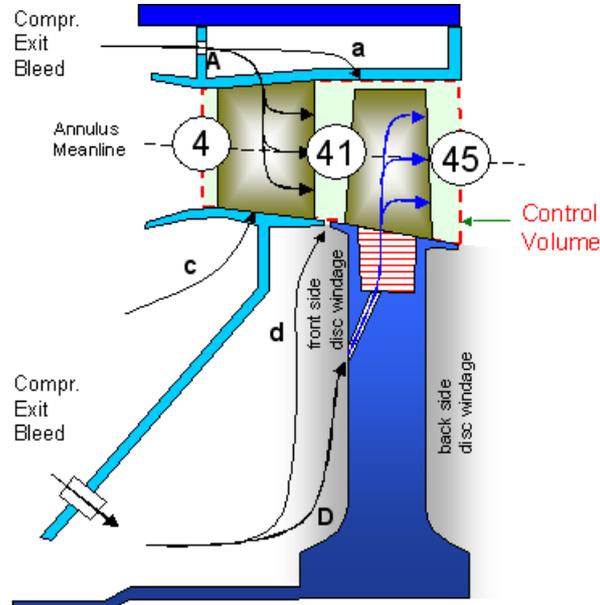
### 4.2.2 Single Stage Turbine

The figure shows a cooled single-stage turbine with a typical cooling air supply system. Compressor exit bleed is the source of the cooling air, and the control volume is identical to the turbine annulus. The power created within the control volume must be bigger than the net power available at the shaft because disk windage and accelerating the cooling air to blade velocity requires some power.

With the most widely used efficiency definition, described for example in [Reference 1](#), for each cooling air stream it is considered whether it does work in the turbine or not. For example, all stator (vane) cooling air is said to do work in the rotor. Thus the rotor inlet temperature (**RIT**, also called stator outlet temperature **SOT** or  $T_{41}$ ) is calculated by mixing energetically the mass flow  $W_4$  with the stator vane cooling air  $W_A$ :

$$h(T_{41}) = \frac{W_4 \cdot h(T_4) + W_A \cdot h(T_3)}{W_4 + W_A}$$

Platform cooling air  $W_c$  and disk rim sealing air  $W_d$  are usually not considered when  $T_{41}$  is calculated since these parasitic flows do not have the potential to do work in the rotor because of lack of momentum. Also the rotor cooling air  $W_D$  and the liner cooling air  $W_a$  cannot do any useful work in the rotor. Therefore these streams are not considered while calculating the expansion process from station 41 to station 415. They are mixed energetically together with the above mentioned parasitic flows downstream of the rotor between stations 415 and 45.



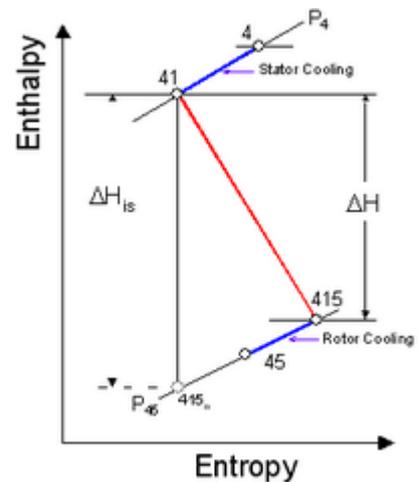
This calculation is shown in the following enthalpy-entropy diagram. The stage efficiency is calculated by:

$$\eta_{stage} = \frac{PW_{SD}}{W_{41} \cdot \Delta H_{is}}$$

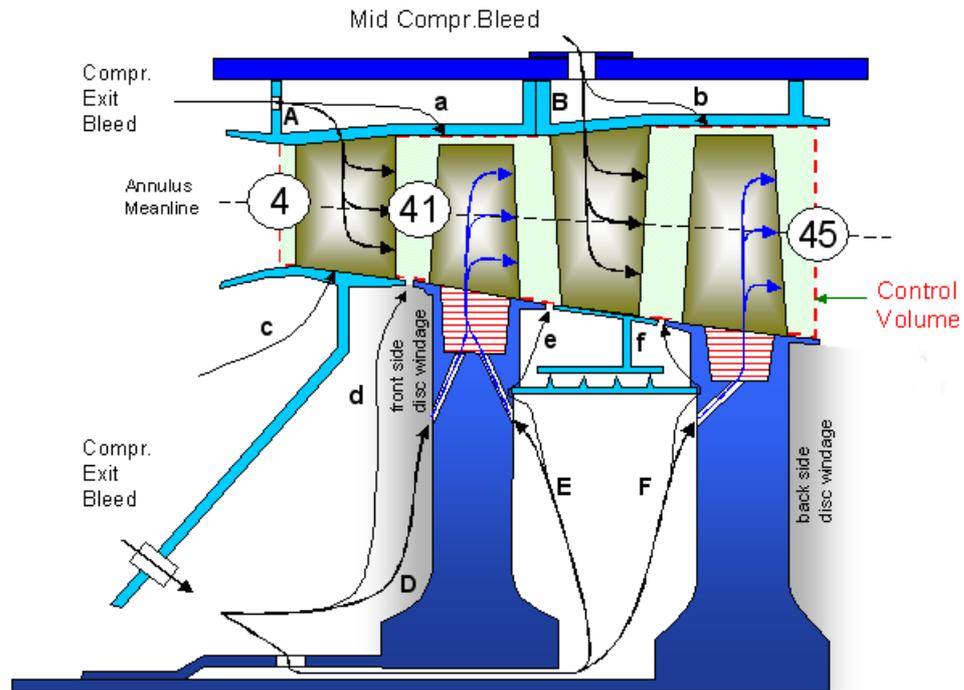
with

- $PW_{SD}$  Shaft power delivered
- $H_{is}$  Isentropic specific work of rotor mass flow for the expansion to P45

With this approach the expansion process in the rotor is the same as in an uncooled turbine, and therefore the number used for the efficiency can be understood as that for an uncooled turbine.



### 4.2.3 Two Stage Turbine



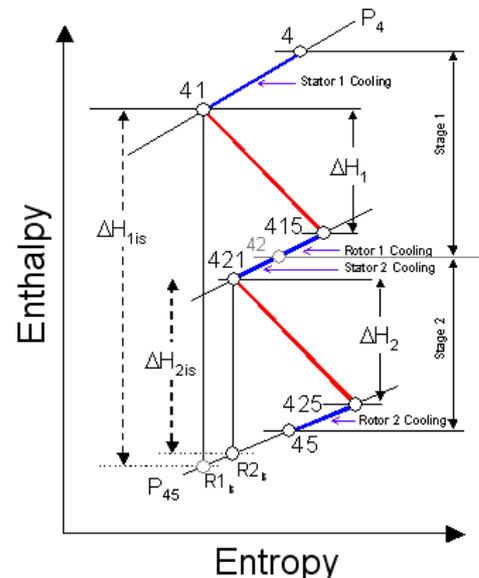
The figure shows the schematic of a two-stage cooled turbine with many secondary air streams. Such a turbine can be modeled with two different approaches. In the first approach the two-stage turbine is simulated as an equivalent single-stage turbine. Each secondary flow is assigned a work potential. For example, the work potential of the first rotor cooling air will be approximately 50% as opposed to the 0% for a true single-stage turbine. Consequently the calculated rotor inlet temperature will no longer be equal to the true stator exit temperature  $T_{41}$  because more than just the stator cooling air must be mixed with the main stream to get the equivalent rotor inlet temperature  $T_{41eq}$ . This temperature is used to calculate the expansion process through the equivalent single-stage turbine.

$$\eta = \frac{PW_{SD}}{W_{41} \cdot \Delta H_{1is} + (W_{421} - W_{415}) \cdot \Delta H_{2is}}$$

with

- $PW_{SD}$  Shaft power delivered
- $H1_{is}$  Isentropic specific work of rotor 1 mass flow for the expansion to  $P_{45}$
- $H2_{is}$  Isentropic specific work of rotor 2 mass flow added between stations 421 and 425

The calculation - which is implemented in GasTurb - is basically the same as sketched in the h-s diagram for a [single stage turbine](#) and yields for given total turbine power and pressure ratio the **equivalent stage efficiency** of the turbine.

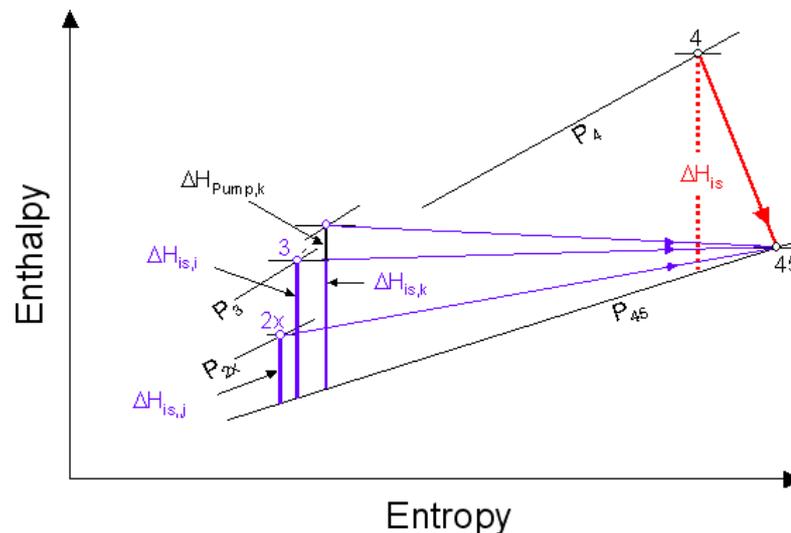


The second approach to model the two-stage cooled turbine - which is not supported by GasTurb - follows the path shown in the h-s diagram above. Each stage is modeled separately and the secondary airflows are mixed with the main stream at the appropriate stations. The cooling air of the first vane is mixed upstream of the first rotor, and the rest of the first stage secondary flows are mixed immediately downstream of the first rotor (station 42 in the first figure). Next the cooling air of the second vane is mixed, which yields the inlet mass flow  $W_{421}$  for the second rotor. At the exit of the second rotor the rest of the secondary airflows are mixed with the mainstream.

With this approach one can study the effects of cooling air in a more direct way than with the equivalent single-stage approach. This, however, comes at a price: one needs to know the efficiency of each individual stage as well as the work distribution between the two rotors. During off-design simulations one needs two turbine maps, one for each stage. These maps cannot be derived from engine tests because the required instrumentation is not available. Maps from a rig test are not fully representative because in such a test the cooling air effects on the flow are nearly never properly simulated because the temperature ratios between the cooling air and the main stream are not as in the engine. Moreover, the map of the second stage is affected by the variable exit swirl of the first stage and therefore theoretically several maps for selected inlet swirl angles are required.

#### 4.2.4 Thermodynamic Turbine Efficiency

The second most used efficiency definition for a cooled turbine is called in literature the **thermodynamic efficiency**. In this approach the turbine is dealt with as a black box which converts thermal energy into shaft power. The input into this black box are the main stream energy flow  $W_4 \cdot h(T_4)$  and many secondary air streams  $W_i \cdot h(T_i)$ . All of these energy streams have the work potential which results from an isentropic expansion from their individual total pressure  $P_i$  to the turbine exit pressure  $P_{45}$ .



The cooled turbine process is shown in the enthalpy-entropy diagram above. The thermodynamic efficiency is defined as:

$$\eta_{th} = \frac{PW_{SD} + PW_{pump}}{W_4 \cdot \Delta H_{is} + \sum W_i \cdot \Delta H_{is,i} + \sum W_k \cdot \Delta H_{pump,k}}$$

$PW_{pump}$  is the shaft power required to accelerate the rotor cooling air to blade velocity.

The advantage of this turbine efficiency definition is that no assumptions have to be made about the work potential of the individual secondary streams. The work potential of these streams is defined via their respective pressures and temperatures, which at least theoretically all can be measured. Thus the use of the thermodynamic turbine efficiency is less ambiguous than all the other methods mentioned above. Moreover, the thermodynamic turbine efficiency accounts for the pressure of the secondary streams while all the other definitions do not. Note that within this definition no stator outlet temperature needs to be calculated.

The thermodynamic turbine efficiency is calculated within GasTurb and offered as an output property for analysis or for being used as iteration target.

## 4.2.5 Calculation Options in GasTurb Details

### 4.2.5.1 Turbine Stage Number and Tabular Data Input

When you come first time to the cooled turbine main window you must load one of the data sets. There are demo data sets for single stage turbines, two-stage turbines and three stage turbines. If you work with a turbine which has more than three stages then use the three-stage turbine example. When you use GasTurb Details 6 for the first time then open one of the demo data sets. Load the file **Demo2Stg.TEF** which contains data for a two-stage turbine, for example. Note that after having loaded a TEF file you can switch to a different number of stages by clicking the corresponding **Stage Count** button.

The nomenclature for the cooling air system is presented in a dedicated window, click the **Key** symbol to the right of the stage count buttons for opening that window. The numbers entered there are also shown in the top left table of the main "Cooled Turbine" window.

Stream		% of W25
A	NGV Cooling	5,5
a	Blade 1 Shroud Cooling	0,5
B	Vane2 Cooling	2
b	Blade 2 Shroud Cooling	0,3
c	NGV Platform Leak	0,4
D	Blade 1 Cooling (front)	5
d	Disc 1 Rim Seal (front)	0,6
E	Blade 1 Cooling (back)	0
e	Disc 1 Rim Seal (back)	0,2
F	Blade 2 Cooling	2
f	Disc 2 Rim Seal (front)	0,25
	Total	16,75

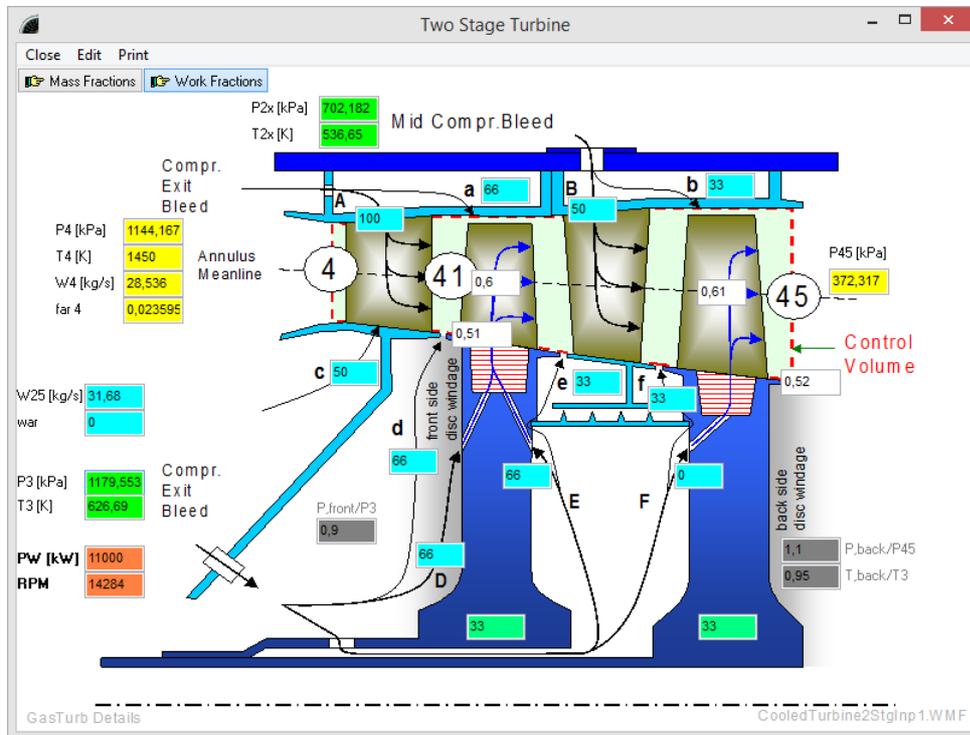
Further tabular input opportunities are grouped together in the notebook on the right side of the main "Cooled Turbine" window:

Main Stream	Pumping	Windage	Work Distr.
Inlet Press. P4 [kPa]			1144,167
Inlet Temp. T4 [K]			1450
Inlet Mass Flow W4 [kg/s]			28,536
Inlet Fuel-Air_Ratio far4			0,023595
Power Delivered [kW]			11000
Spool Speed [RPM]			14284
Exit Press. P45 [kPa]			372,317
Compr.Reference Flow W25 [kg/s]			31,68
Water-Air-Ratio war			0
Compr.Delivery Press. P3 [kPa]			1179,553
Compr.Delivery Temp. T3 [K]			626,69
Compr.Midstage Press. P2x [kPa]			702,182
Compr.Midstage Temp. T2x [K]			536,65

The numbers in the tables can be modified. After editing numbers in a table it is necessary that the data presented elsewhere are updated. Click the **Calculate** button for that.

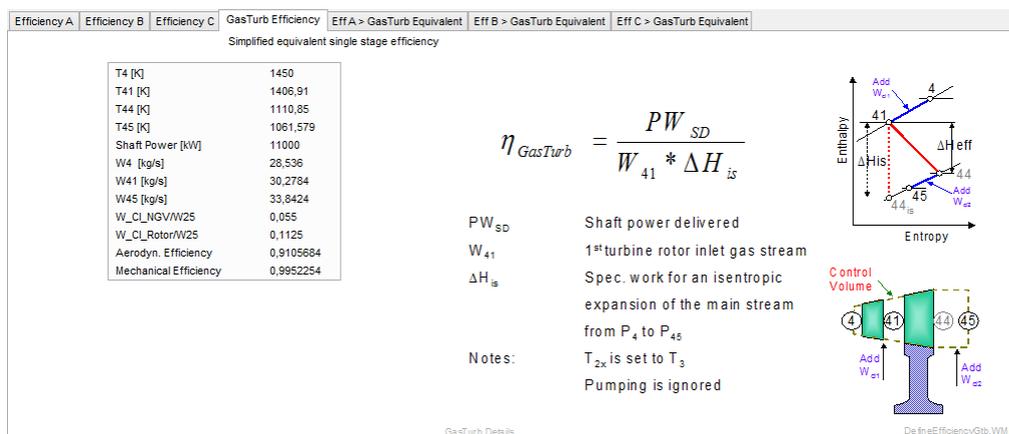
### 4.2.5.2 Data Input in a Cross Section

For some of the cooled turbine efficiency methodologies one must assign each of the cooling air streams a work potential. A number between 0 and 100 must be used for that. Switch in the nomenclature window between **Mass Fractions** input and **Work Fractions** input. Note that the work fractions can only be modified here.



### 4.2.5.3 Efficiency Definition Options

Four different options for defining the efficiency of a cooled turbine are implemented. Click one of the four leftmost tabs of the notebook at the bottom of the "Cooled Turbine" window and you get besides the numbers also a graph with the corresponding definition of efficiency. Click the graph to enlarge it for better visibility.



#### 4.2.5.4 Correlations Between Efficiencies

The number for the efficiency of a cooled turbine depends on the simulation methodology employed. In the lower part of the "Cooled Turbine" window you find the numbers for each of the efficiency definitions. Especially you find for each of the definitions a table with the numbers to be used with GasTurb which employs the equivalent single stage efficiency definition.

Efficiency A	Efficiency B	Efficiency C	GasTurb Efficiency	Eff A > GasTurb Equivalent	Eff B > GasTurb Equivalent	Eff C > GasTurb Equivalent	
<b>Efficiency A:</b> T4 [K] 1450 T41 [K] 1406,91 Tin, equivalent [K] 1385,19 T45 [K] 1061,579 Shaft Power [kW] 11000 Is. Main Stream Power [kW] 11745,35 Is. Cooling Air Power [kW] 1330,268 Aerodyn. Efficiency 0,8757407 Mechanical Efficiency 0,9954125				=	<b>Equivalent GasTurb Input:</b> T4 [K] 1450 T41 [K] 1351,832 T44 [K] 1076,207 T45 [K] 1061,579 Shaft Power [kW] 11000 W4 [kg/s] 28,536 W41 [kg/s] 32,80036 W45 [kg/s] 33,8424 W_CL_NGV/W25 0,1346072 W_CL_Rotor/W25 0,03289279 Aerodyn. Efficiency 0,8757407 Mechanical Efficiency 0,9952254		

### 4.3 Heat Exchanger

Heat exchanger effectiveness relates the heat transferred to the maximum amount of heat which can be transferred. The latter can be defined either by the cold or the hot side of the heat exchanger:

$$Q_{\max} = \min \left\{ \begin{array}{l} c_{p,cold} \cdot W_{cold} \cdot (T_{hot,in} - T_{cold,in}) \\ c_{p,hot} \cdot W_{hot} \cdot (T_{hot,in} - T_{cold,in}) \end{array} \right\}$$

For the evaluation of the specific heat the mean temperature on the cold respectively hot side is used.

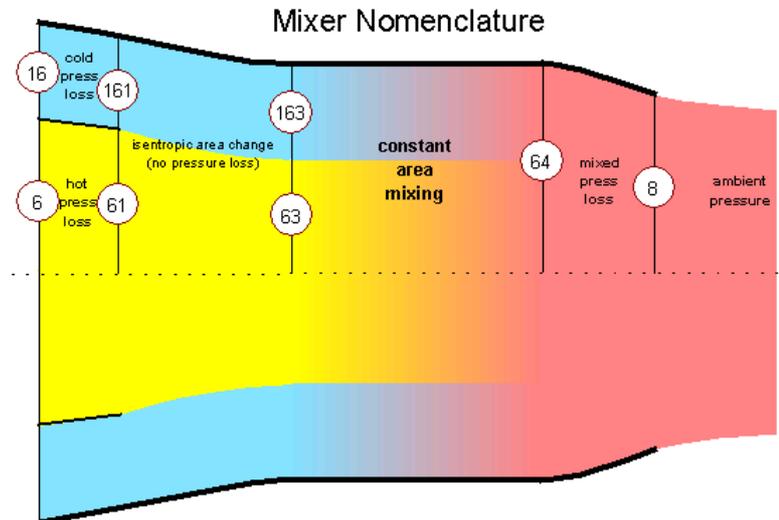
Cold Side Mass Flow	Wc	kg/s	100
Cold Side Inlet Temperature	Tc,1	K	500
Cold Side Water-Air-Ratio	war,c		0
Hot Side Mass Flow	Wh	kg/s	100
Hot Side Inlet Temperature	Th,1	K	1000
Hot Side Fuel-Air-Ratio	far,h		0,025
Hot Side Water-Air-Ratio	war,h		0
Effectiveness	eta		0,8
Cold Side Exit Temperature	Tc,2	K	0
Hot Side Exit Temperature	Th,2	K	0
Heat Transferred	Q	kW	0

The input data for a heat exchanger simulation are listed in the upper table and the results are presented in the lower table.

## 4.4 Mixer

### 4.4.1 Mixing Simulation Methodology

The ideal mixer has no pressure losses from stations 6 to 61, 16 to 161 and 64 to 8. At station 64 both streams are fully mixed and expand as a single stream without any losses through the nozzle. The total pressure and temperature of the cold stream in station 163 are the same as at station 16 and the equivalent is true for the hot stream.



The ideal mixing is taking place in a frictionless duct with constant area. The following laws of physics are applied:

**Conservation of mass:**

$$W_{63} + W_{163} = W_{64}$$

**Conservation of energy:**

$$W_{63} \cdot H_{63} + W_{163} \cdot H_{163} = W_{64} \cdot H_{64}$$

**Conservation of momentum:**

$$W_{63} \cdot V_{63} + P_{s,63} \cdot A_{63} + W_{163} \cdot V_{163} + P_{s,163} \cdot A_{163} = W_{64} \cdot V_{64} + P_{s,64} \cdot A_{64}$$

Furthermore the sum of the cold and hot mixing areas is equal to the total area and the static pressures of both streams are equal:

$$A_{63} + A_{163} = A_{64}$$

$$P_{s,63} = P_{s,163}$$

This system of equations can only be solved by iteration.

The flow is expanded from the conditions at station 8 through the nozzle to ambient pressure and we get the gross thrust for the fully mixed flow. The gross thrust which could be developed by expanding the hot flow from station 6 through the same type of nozzle is called the **hot thrust**  $F_{g,h}$ . Similarly the cold stream expanded from station 16 yields the **cold thrust**  $F_{g,c}$ . The unmixed thrust is the sum of  $F_{g,h}$  and  $F_{g,c}$ .

Mixing efficiency is defined as:

$$\eta_{mix} = \frac{F_g - F_{g,unmixed}}{F_{g,fullymixed} - F_{g,unmixed}}$$

#### 4.4.2 Mixer Input Data

Cold Flow	kg/s	100
Cold Temperature	K	450
Cold Pressure	kPa	200
Cold Mach No. Station 161		0
Cold Area Station 161	m <sup>2</sup>	0,526
Cold Press Loss (P16-P161)/P16		0,01
Hot Flow	kg/s	20
Fuel-Air-Ratio		0,02
Hot Temperature	K	1000
Hot Pressure	kPa	190
Hot Mach No. Station 61		0
Hot Area Station 61	m <sup>2</sup>	0,129
Hot Press Loss (P6-P61)/P6		0,01
Mixed Mach No.		0
Mixer Area	m <sup>2</sup>	0,64
Mixed Press Loss (P64-P8)/P64		0
Ambient Pressure	kPa	101
Mixing Efficiency	%	70

Note that you can specify either the Mach number or the area, but not both:

Hot Mach No. Station 61 **or** Hot Area Station 61

Cold Mach No. Station 161 **or** Cold Area Station 161

Mixed Mach Number **or** Mixer Area (Station 64)

## 4.5 Nozzle

### 4.5.1 Convergent Nozzle

The basic setup of the calculation in GasTurb Details 6 is for a [convergent-divergent nozzle](#).

For a convergent nozzle the exit area ratio  $A_9/A_8$  must be set to 1.0. The calculation is fairly simple: first an isentropic expansion to ambient pressure is calculated. If the resultant Mach number is subsonic, then the static conditions in the nozzle exit plane have already been found. Otherwise the nozzle exit Mach number is set to 1.0 and from this condition new values for  $T_{s,8}$  and  $P_{s,8}$  are calculated.



### 4.5.3 Output Summary Table

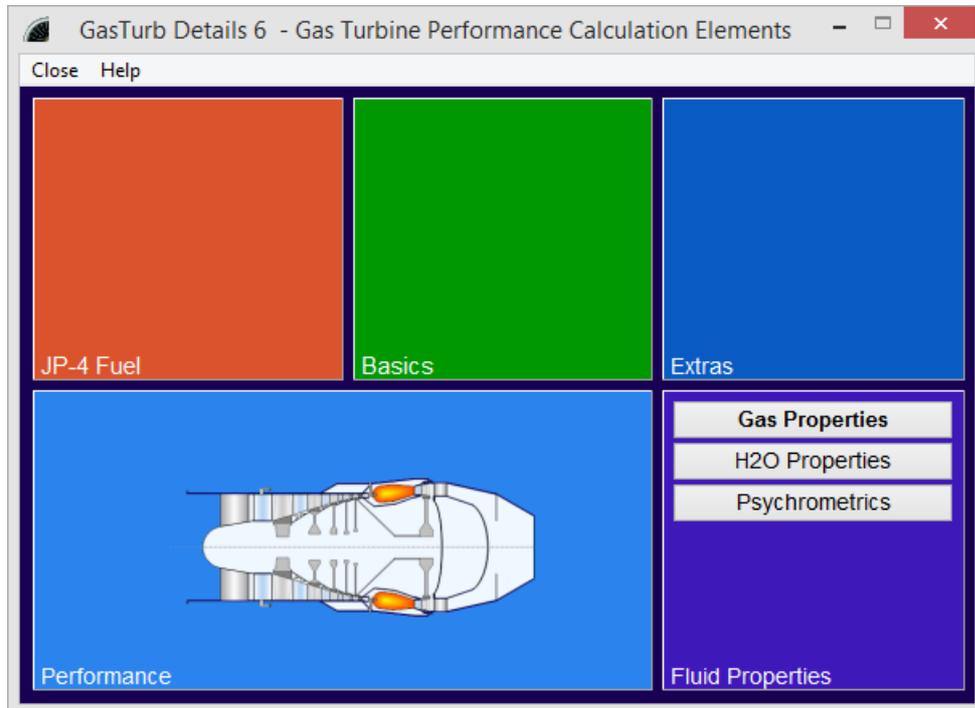
The calculated data are presented in a summary table:

Inlet Total Temperature								
Fuel-Air-Ratio								
Ambient Pressure								
Pressure Ratio								
Throat Area								
Inlet Area Ratio								
Exit Area Ratio								
Inlet Total Temperature								
Fuel-Air-Ratio								
Ambient Pressure								
Pressure Ratio								
Throat Area								
Inlet Area Ratio								
Exit Area Ratio								
Station	W	Ts	P	Ps	Mach	V	Area	
	kg/s	K	kPa	kPa		m/s	m <sup>2</sup>	
inlet	75,3	956,81	400,000	334,365	0,526	317,35	0,19500	
throat	75,3	858,06	400,000	215,670	1,000	573,59	0,15000	
exit	75,3	658,80	400,000	77,056	1,738	880,42	0,21000	
Gross Thrust			61,51					
Pressure Term			-4,82					
Ideal Thrust Coefficient			0,99519					

The ideal thrust coefficient relates the gross thrust of a nozzle to the thrust which could be achieved by expanding the flow ideally to ambient pressure. It is equal to 1.0 if the exit area ratio  $A_9/A_8$  of a convergent-divergent nozzle is such that in the nozzle exit plane  $A_9$  the static pressure is equal to the ambient pressure.

## 5 Fluid Properties Panel

The lower right panel offers access to the fluid properties which are relevant for gas turbine and combined cycle performance:



### 5.1 Gas Properties

#### 5.1.1 The Half-Ideal Gas

Any accurate cycle calculation program must use a good description of the gas properties. In GasTurb the working fluid is assumed to behave like a half-ideal gas. The definition of such a gas can be derived from basic thermodynamics as follows.

The state of a thermodynamic system is described fully by two state variables. For example, enthalpy  $h$  may be written as a function of temperature and pressure:

$$h = h(T, P)$$

The total differential of this relationship is

$$dh = \left( \frac{\partial h}{\partial T} \right)_{P=const} dT + \left( \frac{\partial h}{\partial P} \right)_{T=const} dP$$

Specific heat at constant pressure is defined by

$$\left( \frac{\partial h}{\partial T} \right)_{P=const} = C_p$$

The specific heat at constant pressure  $C_p$  of a real gas depends on both temperature and pressure. Furthermore,

$$\left(\frac{\partial h}{\partial P}\right)_{T=const} \neq 0$$

For an ideal gas  $C_p$  is constant and

$$\left(\frac{\partial h}{\partial P}\right)_{T=const} = 0$$

We now introduce the **half-ideal gas** for which the following relations hold:

$$C_p = f(T)$$

$$C_p \neq f(P)$$

$$\left(\frac{\partial h}{\partial P}\right)_{T=const} = 0$$

Dry air behaves very much like a half-ideal gas at temperatures above approximately 200K. Combustion products have properties that are depended of the chemical composition of the **fuel**, the fuel-air-ratio and temperature.

### 5.1.2 Enthalpy

The enthalpy of the **half-ideal gas** is the integral of  $C_p dT$  where  $C_p$  is the specific heat at constant pressure and  $T$  the temperature. The integration begins at a reference temperature and ends at the temperature of interest:

$$h(T) = \int_{T_{ref}}^T C_p(T) dT$$

The reference temperature  $T_{ref}$  can be selected arbitrarily. Its magnitude is not important for isentropic compression and expansion calculations because these involve only enthalpy differences.

Since the specific heat is a function of temperature and fuel-air-ratio, also the enthalpy is dependant from temperature and fuel-air-ratio.

### 5.1.3 Entropy Function

For an isentropic process with the **half-ideal gas** the following relationship holds

$$\frac{dP}{P} = \frac{C_p(T)}{R} \frac{dT}{T}$$

In integral form this is

$$\int_{P_1}^{P_2} \frac{dP}{P} = \frac{1}{R} \int_{T_1}^{T_2} \frac{C_p(T)}{T} dT$$

We now define the entropy function  $\psi$  as

$$\Psi(T) = \frac{1}{R} \int_{T_{ref}}^T \frac{C_p(T')}{T'} dT'$$

The reference temperature can be selected arbitrarily. Just as for the enthalpy, the calculation of isentropic compression and expansion processes uses only differences of entropy function values, not the absolute values themselves.

Use of the entropy function allows us to write the following simple formula for an isentropic change of state:

$$\ln\left(\frac{P_2}{P_1}\right) = \Psi_2 - \Psi_1$$

Since the specific heat is a function of temperature and fuel-air-ratio, also the entropy function is dependant from temperature and fuel air ratio.

### 5.1.4 Isentropic Exponent

The isentropic exponent is a function of temperature and fuel-air-ratio. It is used within GasTurb only for a few less important calculations. All important calculations are performed with the help of [enthalpy](#) and [entropy function](#).

### 5.1.5 Numbers for Gas Properties

Temperature	K	288,15
Fuel-Air-Ratio		0
Water-Air-Ratio		0
Pressure	kPa	101,325
Specific Heat	J/(kg*K)	1004,516
Isentropic Exponent		1,400066
Enthalpy	J/kg	-10032,34
Entropy Function		-0,1192399
Gas Constant	J/(kg*K)	287,0502
Viscosity	N*s/m <sup>2</sup>	1,801563E-05
Density	kg/m <sup>3</sup>	1,225011
Reynold's No. Index		0,9999983
Rel Humidity	%	0

Enter in the top rows the temperature, the fuel-air-ratio, the water-air-ratio and the pressure, then click the **Calculate** button. All calculations are done with the correlations of the [half-ideal gas](#) employing enthalpy and the entropy function. When you need the data in other units then click on the button with the red arrow or the menu item Units.

The Reynolds Number Index RNI is the ratio of the Reynolds number at a given condition divided by the Reynolds number at sea level static conditions on an ISA day.

## 5.2 Steam Properties

The steam properties as used in GasTurb and GasTurb Details 6 are based on the publications of the International Association for the Properties of Water and Steam (IAPWS), Ref.7. The formulas have been published in August 2007 in the document iapwsif971.pdf which can be downloaded from <http://www.cheresources.com/iapwsif97.shtml>.

Enthalpy-Entropy	Temperature-Entropy	Numbers	
Temperature	C	500	Overheated Steam
Pressure	kPa	1000	
Enthalpy	kJ/kg	3479	
Entropy	kJ/kg	7,764	
Specific Heat @ Const Press	J/(kg*K)	2168,2	
Saturation Temp @ Pressure	C	179,89	
Saturation Pressure @ Temp	kPa		
Density	kg/m³	2,824	

## 5.3 Psychrometrics

Psychrometrics describes the properties of mixtures of water vapor and air. A **Psychrometric Chart** is a graph of the thermodynamic parameters of moist air at a constant pressure. The following terms are used:

### Dry-bulb temperature

When people refer to the temperature of the air, they are normally referring to its dry bulb temperature. This temperature is measured using a normal thermometer freely exposed to the air.

### Wet-bulb temperature

This temperature is indicated by a thermometer with the bulb wrapped in wet muslin. The adiabatic evaporation of water from the thermometer has a cooling effect and therefore the "wet bulb temperature" is lower than the "dry bulb temperature". The rate of evaporation from the wet bandage on the bulb depends on the humidity of the air. The evaporation is reduced when the air contains more water vapor.

### Dew point temperature

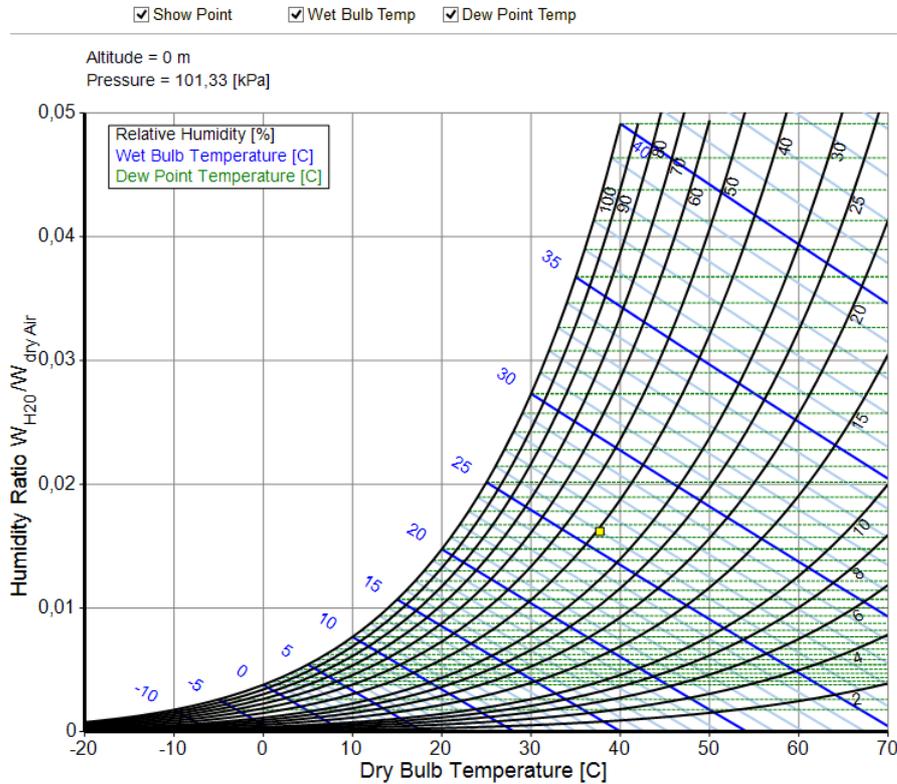
The temperature at which water vapor starts to condense out of the air. The dew point is given by the saturation line (=line for 100% relative humidity) in the psychrometric chart.

### Relative humidity

The ratio of the vapor pressure of moisture in the sample to the saturation pressure at the dry bulb temperature of the sample.

### Humidity Ratio

Humidity ratio is defined as the proportion of the mass of water vapor per unit mass of the dry air sample. In GasTurb the term water-air-ratio is used for the humidity ratio.



Various input parameter combinations can be selected:

Altitude	m	0	<input checked="" type="radio"/> input
Atmospheric Pressure	kPa	101,33	<input type="radio"/> input
Dry Bulb Temperature	C	37,7	<input type="radio"/> input
Wet Bulb Temperature	C	26,193	<input checked="" type="radio"/> input
Relative Humidity [%]		40	<input type="radio"/> input
Dew Point Temperature	C	21,771	<input checked="" type="radio"/> input
Water-Air-Ratio		0,01652338	<input type="radio"/> input
Partial Vapor Pressure	kPa	2,6072	
Saturated Vapor Pressure	kPa	6,518	

### Relevance for gas turbine performance

The cycle of a gas turbine is affected by the properties of the gas (the working fluid). The relevant parameter is the water-air-ratio  $w_{ar}$  (the humidity ratio). In gas turbines used for flight propulsion the water-air-ratio of the working fluid gas usually depends on the weather only.

### Water and Steam Injection

In land based gas turbines used for power generation, water or steam is sometimes injected upstream of the compressor (for power increase), in the combustion chamber (for NOx reduction) or in the turbine (for cooling purposes).

### Inlet Fogging

Water is injected in form of fine droplets (creating fog) in the filter house of the gas turbine. The fog evaporates and cools down the air before it enters the gas turbine. The achievable temperature drop can be found with the help of the psychrometric chart as follows:

Outside of the filter house there is a certain air temperature, which is measured with a thermometer which has a dry bulb. This air contains some water vapor the amount of which is described by the relative humidity. The two parameters dry bulb temperature and relative humidity fix a point in the psychrometric chart. At this point

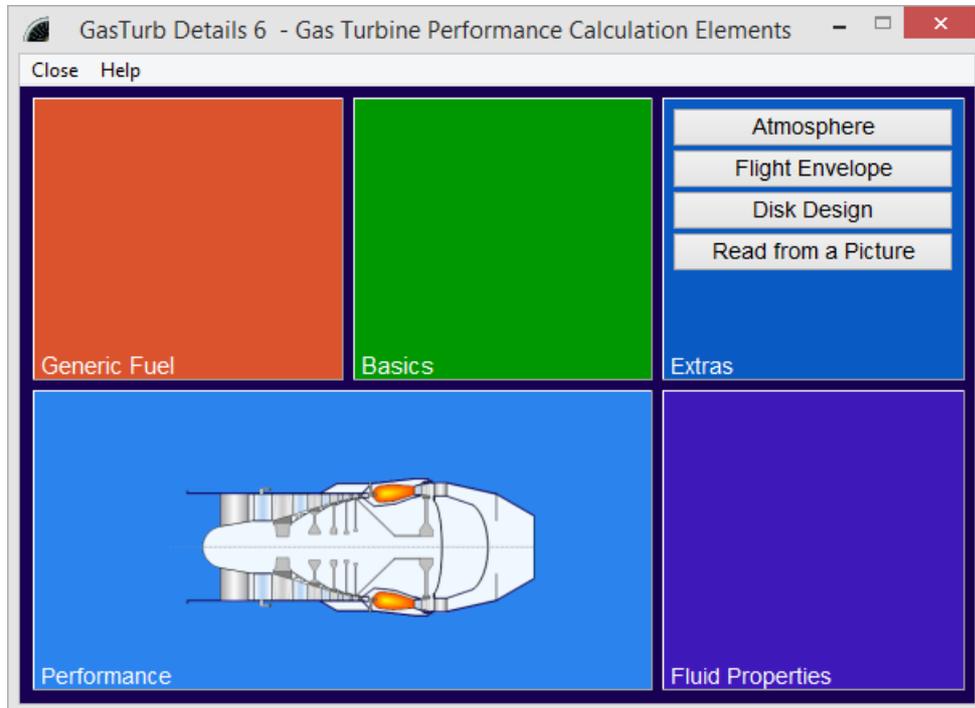
Fogging increases the relative humidity in the ideal case up to 100%. During the fogging process the wet bulb temperature remains constant.

Example:

Air temperature (dry bulb temperature) = 40°C, relative humidity 30%: wet bulb temperature = 25°C

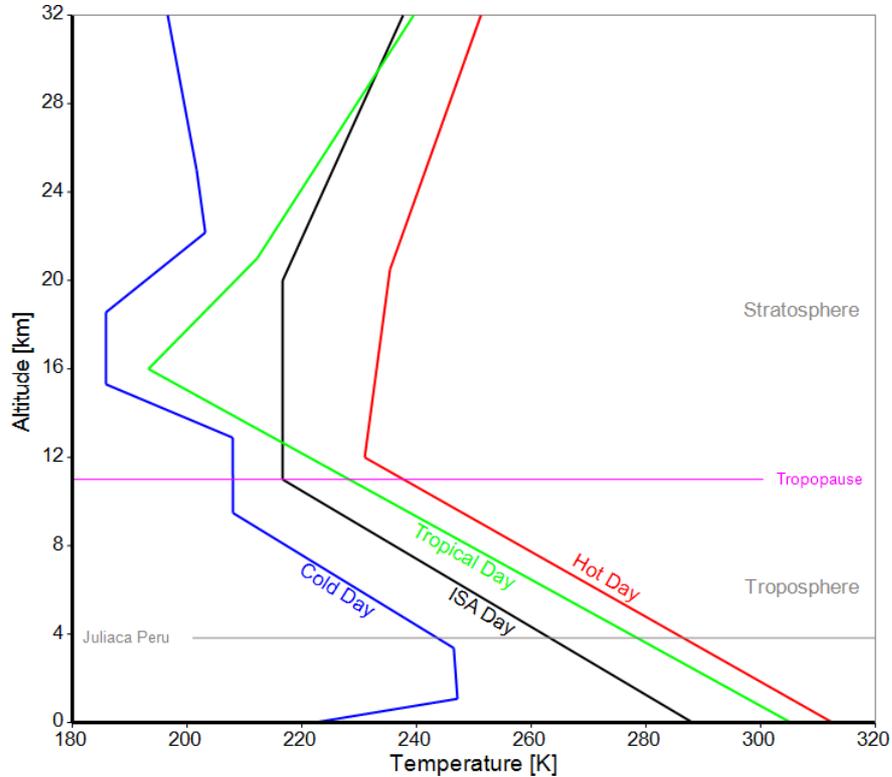
## 6 Extras Panel

On the top right panel there is the access to **Atmosphere** and **Flight Envelope** data. **Detailed Disk Design** studies are possible. **Read from a Picture** leads to a window where you can digitize a picture.



## 6.1 Atmosphere

Temperature, pressure, density and velocity of sound vary in the atmosphere differently on ISA, Cold, Hot and Tropical days. The altitude of some remarkable airports can be shown in the main atmosphere graphic.



Single point data are calculated when you modify the altitude, select a different climate or a new airport.

Temperature	Pressure	Density	Velocity of Sound	Numbers
Altitude [m]		Airport		
3825		Juliaca Peru		
<input checked="" type="radio"/> ISA Day <input type="radio"/> Cold Day <input type="radio"/> Hot Day <input type="radio"/> Tropical Day				
Temperature	T	K	263,2875	
T - T,ISA	T-T,ISA	K	0	
Pressure	P	kPa	63,05901	
Density	rho	kg/m <sup>3</sup>	0,8343706	
Sonic Velocity	V	m/s	325,3286	
Relativized Temperature	T/Tstd		0,9137168	
Relativized Pressure	P/Pstd		0,622344	

## 6.2 Flight Conditions

Within the flight envelope the following quantities at an aircraft engine intake are shown in graphs:

Total Pressure	Total Temperature	Reynolds No Index	True Air Speed	Corr Power Off Take
----------------	-------------------	-------------------	----------------	---------------------

These quantities are calculated using an isentropic exponent of 1.4. For Mach numbers greater than 1 the total pressure is corrected for shock losses according to

$$P_2/P_1 = 1 - 0.075 \cdot (M - 1)^{1.35}$$

Instead of the graphic you can also select a single condition calculation:

Delta T from ISA	C	0
Mach Number		1
Altitude	m	6000

Static Pressure	kPa	47,18099
Total Pressure	kPa	89,32932
Static Temperature	K	249,15
Total Temperature	K	299,0734
Reynolds Number Index		0,9376789
True Airspeed	m/s	316,4961
Corrected Power Offtake	%	111,3379

### 6.2.1 Aircraft Speed

Various definitions for the speed of an aircraft are in use:

#### True Airspeed

The speed of the aircraft's center of gravity with respect to the air mass through which it is passing.

#### Indicated Airspeed

The speed indicated by a differential-pressure airspeed indicator which measures the actual pressure difference in the pitot-static head. This instrument is uncorrected for instrument, installation and position errors. For this reason it is often called pilot's indicated airspeed.

#### Calibrated Airspeed

The airspeed related to differential pressure by the standard adiabatic formulae. At standard sea level conditions the calibrated airspeed and true airspeed are the same. The calibrated airspeed can be thought of as the indicated airspeed, corrected for instrument errors. It is sometimes called true indicated airspeed.

### Equivalent Airspeed

The equivalent airspeed is a direct measure of the incompressible free stream dynamic pressure. It is defined as the true airspeed multiplied by the square root of the density ratio (air density at some flight altitude over density at sea level). Physically the equivalent airspeed is the speed which the aircraft must fly at some altitude other than sea level to produce a dynamic pressure equal to a dynamic pressure at sea level. At low speeds the calibrated airspeed and the equivalent airspeed are the same. For speeds above Mach 0.3 the two differ because of an error in the differential-pressure measuring device. This error is due to the compressibility of the air at higher speeds which cannot be calibrated into the instrument.

GasTurb employs the true airspeed and the equivalent airspeed, but not the indicated and calibrated airspeeds. If you need to know them, then use composed values.

## 6.3 Disk Design

### 6.3.1 Introduction

In GasTurb, if you select **More** in the program opening window, then you can calculate for many engine configurations the basic geometry of the gas turbine including disk geometry and disk stress. The shape of the disk can be adapted in such a way that the [Design Margin](#) is equal to a specified value, expressed in percent. You can deal with each of the disks separately employing GasTurb Details 6 and feed back the results into the cycle program.

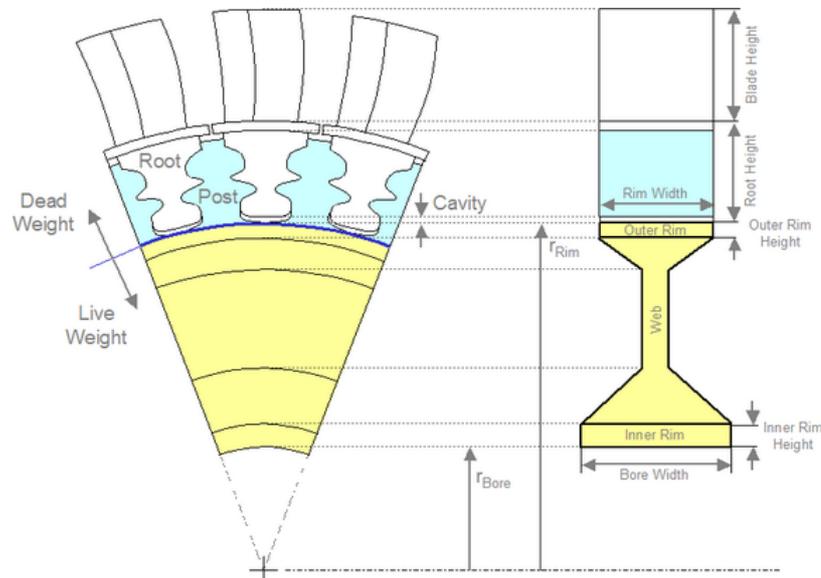
A computer code for gas turbine engine weight and disk life estimation is described in [Reference 6](#). Many of the ideas found there have been used for setting up the disk design algorithms, the help system and the manual of this program. It must be acknowledged that the disk stress calculation methodology employed has its limitations. In an actual disk, the local stresses - which are relevant for disk life - depend on countless details which are not yet known in the preliminary design phase of an engine.

Before any disk calculation can be performed, a disk design data set must be read from file. This can be from a file with input data for a single disk, created with GasTurb Details 6, or from a GasTurb file which can contain the design data of many disks.

From GasTurb Details 6, when you are done with the design of a disk, you can write the optimized geometry either to a new file or you can update the data in the appropriate GasTurb file.

### 6.3.2 Disk Geometry

Disks are divided into two parts: the **live disk** and the part where the blades are attached. The disk stress calculation deals only with the live disk which carries the rim load caused by the blades (including shroud, inner platform and root) and the posts holding the blades. With other words, any material outside of the smallest radius of the cavities (see figure) is dead weight which produces the disk rim load.



**Adapt Bore Width**, **Adapt Bore Radius** and **Optimize Disk** are calculation control variables for GasTurb only, their values have no effect on the calculation in GasTurb Details 6

The **Rim Width** is equal to the axial component of the blade chord. Note that the cavity height is ignored when considering the **Root/Blade Height Ratio**.

### 6.3.3 Material Database

The stresses in the disk and the design margins depend on the material used for manufacturing the disk. The program comes with a material database which contains information from open literature. For most of the materials the temperature dependency of Poisson's ratio could not be found, it was set to the constant value of 0.3.

Although the data is believed to be representative, the characteristics of the actual material may vary from what is contained in the database. The author of the program makes no warranty of any kind and assumes no liability with respect to the accuracy of the material data.

The file **MaterialData.txt** is a pure ASCII file which can be edited from within GasTurb Details 6 or modified with any other text editor. Additional data sets can be appended, the maximum number of data sets is 30. You can also create your own material database and read it before commencing with the calculations.

Each data set must be formatted like the following example:

INCONEL 718				<b>Name of the Material</b>
8220				<b>Density, kg/m<sup>3</sup></b>
100	150	200	250	... <b>Temperature, °C (up to 25 values)</b>
196	193	190.5	188	... <b>Modulus of Elasticity, GPa</b>
13.2	13.35	13.53	13.71	... <b>Coefficient of Expansion, µm/m/°C</b>
0.289	0.283	0.280	0.276	... <b>Poisson's ratio</b>
1170	1150	1130	1110	... <b>Yield Strength, MPa</b>
1385	1375	1360	1352	... <b>Ultimate Strength, MPa</b>
1	11	21	31	... <b>Column</b>

Note that the blue text is for explanation of the file structure only, do not include it in your material database file. Sorry for people who normally do not use SI units: this database must not contain data in US units, only the SI units indicated in the blue explanations are allowed.

If you find graphics with material data in literature, you can scan it and [read the data from the bitmap](#) with GasTurb Details 6!

### 6.3.3.1 INCONEL 601

INCONEL® 601 is a general purpose nickel-chromium-iron alloy for applications that require resistance to heat and corrosion. In gas turbines it is used for combustion-can liners, diffuser assemblies and containment rings.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

### 6.3.3.2 INCONEL 706

INCONEL 706 nickel-iron-chromium alloy provides high mechanical strength in combination with good fabricability. In the aerospace field, the alloy is used for compressor and turbine disks, shafts and cases. In large industrial gas turbines it is used for turbine disks.

The heat treatments used are designed to produce either high stress-rupture properties (INCONEL 706A) for applications up to 705°C (1300°F) or high tensile properties for moderate-temperature applications (INCONEL 706B).

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

[www.hightempmetals.com](http://www.hightempmetals.com)

### 6.3.3.3 INCONEL 718

INCONEL 718 is a high strength, corrosion-resistant nickel chromium material used up to 700°C (1300°F) for rings and casings.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

#### 6.3.3.4 UDIMET R41

Common trade names: **René 41®**, **Allvac René® 41**, **Haynes® R-41**, **Udimet® R41**

UDIMET® R41 is a nickel-chromium alloy with extremely high room and elevated temperature mechanical properties. It is used in critical aircraft engine components such as nozzle partitions, turbine blades and disks, combustion chamber liners and structural hardware.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

[www.hightempmetals.com](http://www.hightempmetals.com)

[www.magellanmetals.com/Rene41.htm](http://www.magellanmetals.com/Rene41.htm)

#### 6.3.3.5 UDIMET 720

UDIMET alloy 720 is a nickel base alloy which combines high strength with metallurgical stability. Good oxidation and corrosion resistance combined with high strength make it useful in gas turbine blade and disk applications.

**Note:**

Unfortunately the temperature dependence of the modulus of elasticity and the thermal expansion coefficient are not contained in the reference. These dependencies have been estimated, and this estimate is certainly inaccurate.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

#### 6.3.3.6 Waspaloy

Waspaloy is a nickel-base superalloy with excellent high-temperature strength and good corrosion resistance at service temperatures up to 650°C (1200°F) for critical rotating applications and up to 870°C (1600°F) for less demanding applications.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

[asm.matweb.com/search/specificMaterial.asp?bassnum=NHWASA](http://asm.matweb.com/search/specificMaterial.asp?bassnum=NHWASA)

#### 6.3.3.7 Haynes 282

Haynes alloy 282 is a superalloy for potential applications in aircraft and land based gas turbines. At high temperatures, even as high as 900°C (1650°F) this alloy is stronger than Hynes Waspaloy and approaches the strength of Haynes R-41 alloy. It has much improved thermal stability, weldability and fabricability compared to Waspaloy and R-41 alloys.

**Source:**

[www.haynesintl.com](http://www.haynesintl.com)

### 6.3.3.8 Greek Ascoloy (418)

Greek Ascoloy (418) is a stainless steel designed for services at temperatures up to 650°C (1200°F). Typical applications in gas turbines are compressor parts.

**Source of Data:**

[www.hightempmetals.com](http://www.hightempmetals.com)

### 6.3.3.9 AM 350

Alloy AM 350 is a chromium-nickel-molybdenum stainless steel which has been used for compressor components such as blades, disks and shafts.

**Source of Data:**

[www.hightempmetals.com](http://www.hightempmetals.com)

### 6.3.3.10 N-155 (Multimet)

N-155 Multimet is recommended for applications involving high stresses at temperatures up to 815°C (1500°F) and can be used up to 1100°C (2000°F) where only moderate stresses are involved. It is used in gas turbines for exhaust manifolds, combustion chambers and turbine blades.

**Source of Data:**

[www.hightempmetals.com](http://www.hightempmetals.com)

### 6.3.3.11 Alloy A-286

The A-286 Iron-Nickel-Chromium alloy is designed for applications requiring high strength and good corrosion resistance at temperatures up to 70°C (1300°F). It has been used in jet engines for turbine wheels and blades, casings and afterburner parts.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

[www.hightempmetals.com](http://www.hightempmetals.com)

### 6.3.3.12 Haynes 188

Haynes 188 is a superalloy with excellent high temperature strength and excellent resistance to oxidizing environments up to 1100°C (2000°F). It is widely used for fabricated parts in gas turbine engines.

**Source of Data:**

[www.specialmetals.com](http://www.specialmetals.com)

[www.haynesintl.com](http://www.haynesintl.com)

### 6.3.3.13 Ti-6Al-4V

This alloy is the workhorse alloy of the titanium industry; It is used up to approximately 400°C (750° F) for blades, discs and rings.

#### Source of Data:

<http://www.stainless-steel-world.net/titanium/alloys.asp>

[www.efunda.com/materials/alloys/titanium](http://www.efunda.com/materials/alloys/titanium)

Various publications

## 6.3.4 Stress Calculation

### 6.3.4.1 Rim Load

The rim load is calculated considering the individual masses of the blades (including the shroud), the blade roots (including the blade platforms) and those parts of the disk that are located between the blade roots, dubbed the posts. For each of these elements the product of mass, center of gravity and rotational speed yield a contribution to the radial forces pulling at the rim of the live disk. The rim stress  $\sigma_{r,rim}$  is the sum of all the forces divided by the live disk rim area.

Besides the flow annulus dimensions and the **number of blades**  $n_b$  only a few more quantities are needed for the rim load estimation. The **Root/Blade Height Ratio** is usually much higher with high pressure turbines compared to low pressure turbines. Note that with **Mean Blade Thickness, [%] of Chord** the thickness of the metal is meant which is in case of cooled or hollow blades less than the mean profile thickness. Furthermore, one should not mix up the profile thickness quoted by the aerodynamicists with the mean blade thickness employed here.

The rim load estimation employs some empirical correlations which can not be representative for every case. However, by using adequate input values for the **Mean Blade Thickness** and the **Root/Blade Height Ratio** a realistic value for the rim load can be achieved.

#### 6.3.4.1.1 Airfoil Mass

At first the true **mean blade chord**  $c_{b,mean}$  is calculated from the axial chord (which is equal to the the rim width  $t_{rim}$ ) assuming 35° stagger angle ( $\cos 35^\circ=0.82$ ):

$$c_{b,mean} = t_{rim} / 0.82$$

Blade taper must be taken into account by using an adequate value for the mean thickness/chord ratio  $(t/c)_{b,mean}$  when calculating the **mean blade material thickness**  $t_b$ :

$$t_b = c_{b,mean} \cdot (t/c)_{b,mean}$$

The **mass of a single airfoil**  $m_{af}$  (made of a material with the density  $\rho_b$ ) is

$$m_{af} = \rho_b \cdot (r_{tip} - r_{root}) \cdot t_b \cdot c_{b,mean}$$

Its center of gravity is more inbound than the mean annulus radius because of blade taper:

$$r_{cg,af} = 0.4 \cdot r_{tip} + 0.6 \cdot r_{root}$$

Blade shrouds, if they exist, are assumed to have a mean thickness which is approximately 5% of the rim width. Thus the mass of a single shroud is:

$$m_{srd} = 0.05 \cdot \rho_b \cdot t_{rim}^2 \cdot (2 \cdot \pi \cdot r_{b,tip}) / n_b$$

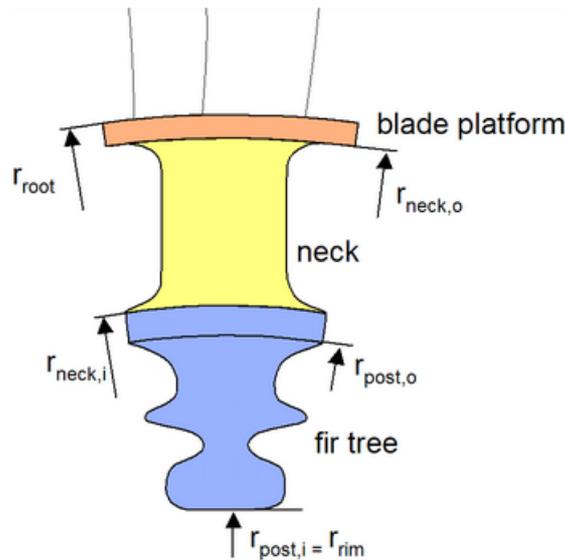
The center of gravity of the shroud is at the radius

$$r_{cg,srd} = r_{tip} + 0.05 \cdot t_{rim}$$

This formula takes into account that the shroud is not only a simple plate, on top of it there are so-called **tip fences** which shift the center of gravity of the shroud to a higher radius than the mean radius of the shroud plate.

### 6.3.4.1.2 Blade Attachment

The blade attachment is comprised of the blade platform, the neck and the fir tree. The neck exists only if the total height of the blade root is bigger than the sum of blade platform thickness and the fir tree height.



The total height of the blade root  $h_{root} = r_{root} - r_{rim}$  is calculated from the given values for blade height and root/blade height ratio. The blade platform thickness  $t_{platform}$  is set to 5% of the rim width. The fir tree height  $h_{fir\ tree} = r_{neck,i} - r_{rim}$  is assumed to be not greater than the blade platform width  $h_{fir\ tree,max} = 2 \cdot \pi \cdot r_{root} / n_b$ . The inner radius of the neck becomes  $r_{neck,i} = r_{rim} + h_{fir\ tree,max}$ . If  $r_{neck,i}$  happens to be greater than  $r_{root} - t_{platform}$  then no neck exists,  $r_{neck,i}$  is set to  $r_{root} - t_{platform}$  and the fir tree height is reduced to  $r_{root} - t_{platform} - r_{rim}$ .

Mass of the blade platform is

$$m_{platform} = 0.05 \cdot \rho_b \cdot t_{rim}^2 \cdot (2 \cdot \pi \cdot r_{root}) / n_b$$

and the fir tree mass is

$$m_{firtree} = \rho_b \cdot t_{rim} \cdot \pi \cdot (r_{neck,i}^2 - r_{rim}^2) / (2 \cdot n_b)$$

The posts extend to the radius  $r_{post,o}$  which is set to  $r_{rim} + 0.8 \cdot (r_{neck,i} - r_{rim})$ . Their mass is (disk material density  $\rho_d$ ):

$$m_{post} = \rho_d \cdot t_{rim} \cdot \pi \cdot (r_{post,o}^2 - r_{rim}^2) / (2 \cdot n_b)$$

If the neck exists, then its thickness is assumed to be twice as that of the blade:

$$m_{neck} = 2 \cdot \rho_b \cdot t_b \cdot t_{rim} \cdot (r_{neck,o} - r_{neck,i})$$

The center of gravity for these elements is assumed to be at their respective mean radius. The total dead mass per blade is

$$m_b = m_{af} + m_{srd} + m_{platform} + m_{neck} + m_{firtree} + m_{post}$$

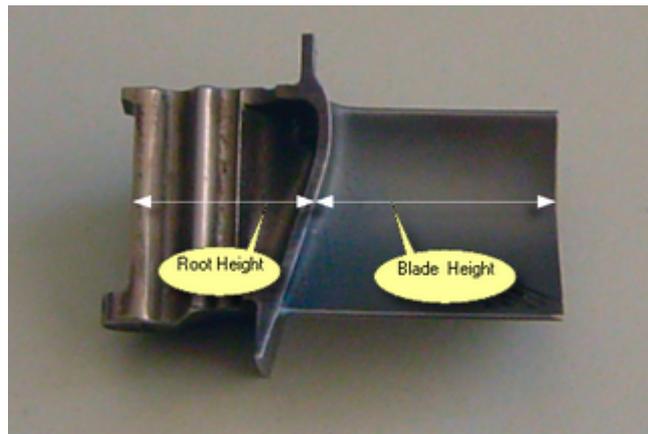
The center of gravity of the dead weight is at the radius:

$$r_{cg,b} = \left( m_{af} \cdot r_{cg,af} + m_{srd} \cdot r_{cg,shr} + m_{platform} \cdot r_{cg,platform} + m_{neck} \cdot r_{cg,neck} + m_{firtree} \cdot r_{cg,firtree} + m_{post} \cdot r_{cg,post} \right) / m_b$$

Finally, the total **rim load** is

$$\sigma_{r,rim} = \frac{n_b \cdot m_b \cdot r_{cg,b}}{2 \cdot \pi \cdot r_{rim} \cdot t_{rim}} \omega^2$$

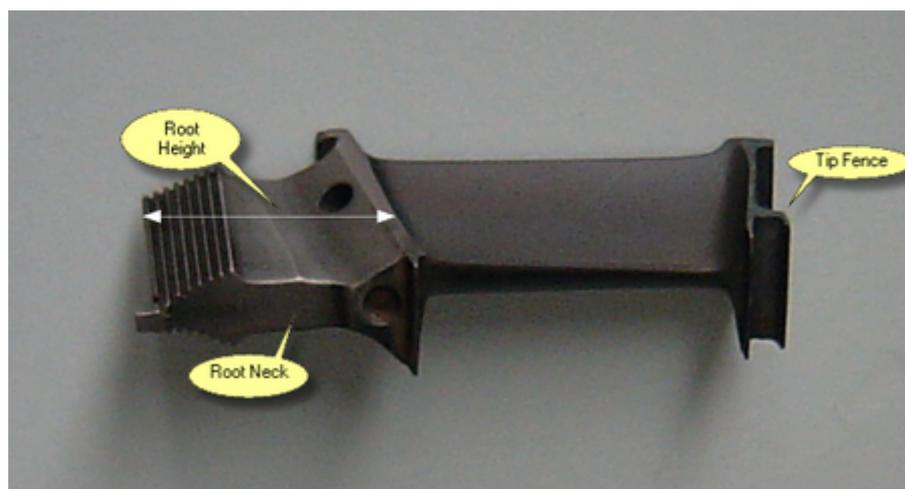
### 6.3.4.1.3 Blade Examples



Unshrouded high pressure turbine blade



Shrouded low pressure turbine blade with two tip fences



Shrouded turbine blade with root neck

### 6.3.4.2 Disk Stress Analysis

The disk stress analysis is based on the following differential equations (see [Reference 6](#)):

Equilibrium of forces for a disk element:

$$\frac{d(t \cdot r \cdot \sigma_r)}{dr} - t \cdot \sigma_t + t \cdot \rho \cdot \omega^2 \cdot r^2 = 0$$

Radial stress:

$$\sigma_r = \frac{E}{1-\nu^2} \left( \frac{du}{dr} + \nu \frac{u}{r} - (1+\nu) \cdot \alpha \cdot \Delta T \right)$$

Tangential Stress:

$$\sigma_t = \frac{E}{1-\nu^2} \left( \frac{u}{r} + \nu \frac{du}{dr} - (1+\nu) \cdot \alpha \cdot \Delta T \right)$$

with

E	N/m <sup>2</sup>	Modulus of elasticity
r	m	Radius
t	m	Disk thickness
u	m	Radial displacement
	1/K	Coefficient of thermal expansion
	-	Poisson's ratio
$\sigma_r$	N/m <sup>2</sup>	Radial stress
$\sigma_t$	N/m <sup>2</sup>	Tangential stress
	rad/s	Rotational speed
T	K	Temperature above reference (room) temperature

For the stress calculation in GasTurb Details 6 the differential equations above are converted into finite difference equations which are applied to many rings in which the live disk is divided. In the disk bore (the inner area of the innermost ring) the radial stress  $\sigma_r$  is zero. When the calculation begins, the displacement of the bore is estimated and the differential equations yield the radial and the tangential stresses as well as the displacement at the outer radius of the first ring. These quantities allow then to calculate the conditions of the second and the further rings. Finally all the rings have been calculated and the radial stress at the outer radius of the live disk is found. As long as this radial stress is not equal to the rim load, the estimated bore displacement is iteratively corrected until the rim load is equal to the calculated radial stress at the outer radius of the live disk.

The temperature distribution in the disk is assumed to vary linearly between the bore and the rim temperatures. The reference temperature is 20°C; for this temperature no stress exists in a non-rotating disk.

### 6.3.4.3 Design Criteria

The disk stress calculation should be done for the maximum steady state rotational speed and the highest operating temperatures. If the operating point with the highest temperature does not coincide with the operating point which has the highest rotational speed then both conditions should be checked.

The disk design margin (expressed in %) compares the yield strength of the material at the local temperature  $\sigma_{0.2,local}$  with the local **von Mises** stress  $\sigma_{vonMises}$ :

$$DM = \left( \frac{\sigma_{0.2,local}}{\sigma_{vonMises}} - 1 \right) \cdot 100$$

The lowest local design margin is presented as output quantity. Moreover, the stress margins at the bore and at the web outer diameter, just below the disk rim, are available as design criteria.

No safety margins are considered, it is up to you to design the disk for the positive stress margin you consider appropriate (10...30% are reasonable numbers).

The disk burst margin (in %) compares the ultimate strength of the material  $\sigma_{ultimate}$  (evaluated at the average disk temperature) with the average tangential stress:

$$BM = \left( \frac{0.47 \cdot \sigma_{ultimate}}{\sigma_{t,average}} - 1 \right) \cdot 100$$

The factor 0.47 (taken from Ref. 6) is a sort of safety margin and therefore Burst Margin  $\geq 0$  is a reasonable design target.

The disk burst speed - which should be greater than 130...150% of the operating speed - is calculated as

$$\frac{\omega_{burst}}{\omega_{op}} = 100 \cdot \sqrt{\frac{\sigma_{ultimate}}{\sigma_{t,average}}}$$

For the optimization of the disk geometry its mass and the polar moment of inertia of the bladed disk are important properties.

### 6.3.5 Optimization

A numerical optimization routine is build into GasTurb Details 6 which allows to optimize the geometry of disks. First select your optimization **variables** and set lower and upper boundaries for these variables. Next choose the **constraints** that are relevant for your problem and finally select a quantity as **figure of merit** which is to be maximized or minimized. Note that the starting point of the optimization must be within the permissible range boundaries of the variables and the constraints.

Two optimization strategies are offered: a gradient strategy and the adaptive random search strategy. On a modern computer the time needed for an optimization is so short that the speed differences between the two strategies is of no relevance. If you are in doubt whether the true optimum has been found, try both strategies. Note that the random search algorithm uses for each run a new set of random numbers and therefore the optimization result will be slightly different for each time you run this algorithm.

The range between the minimum and the maximum values for the optimization variables has an influence on the precision of the result: A small range yields high accuracy, however, there is the danger that unintentionally the true optimum is excluded by too narrow range boundaries.

**Example:**

Variables	Min Value	Start Value	Max Value
Bore Radius Input	0,1	0,15	0,2
Bore Width Input	0,02	0,0309999	0,03
Inner Rim Height/Rim Width	0,5	0,758333	1

**Step 1: Selection of the optimization variables and their boundaries**

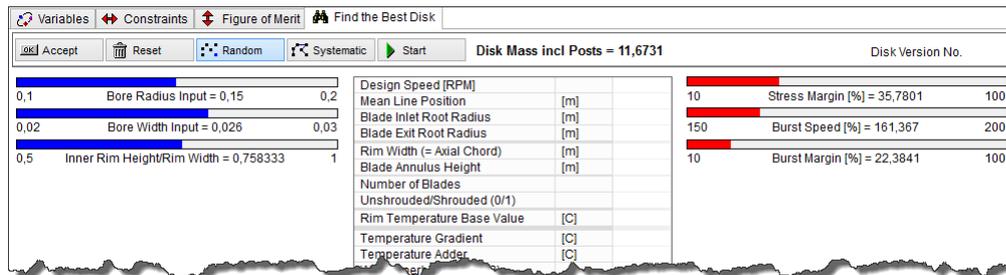
Constraints	Min Value	Start Value	Max Value
Stress Margin [%]	10	43,8904	100
Burst Speed [%]	150	165,976	200
Burst Margin [%]	10	29,4763	100

**Step 2: Selection of constraints**

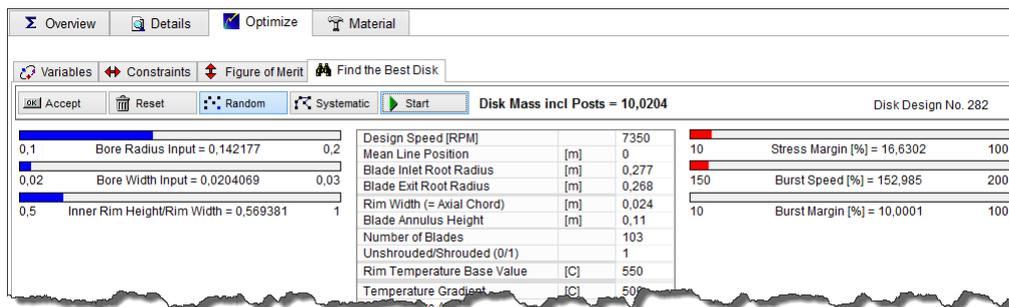
Figure of Merit	Min Value	Start Value	Max Value
Disk Mass incl Posts			

**Step 3: The figure of merit is disk mass which shall be minimized**

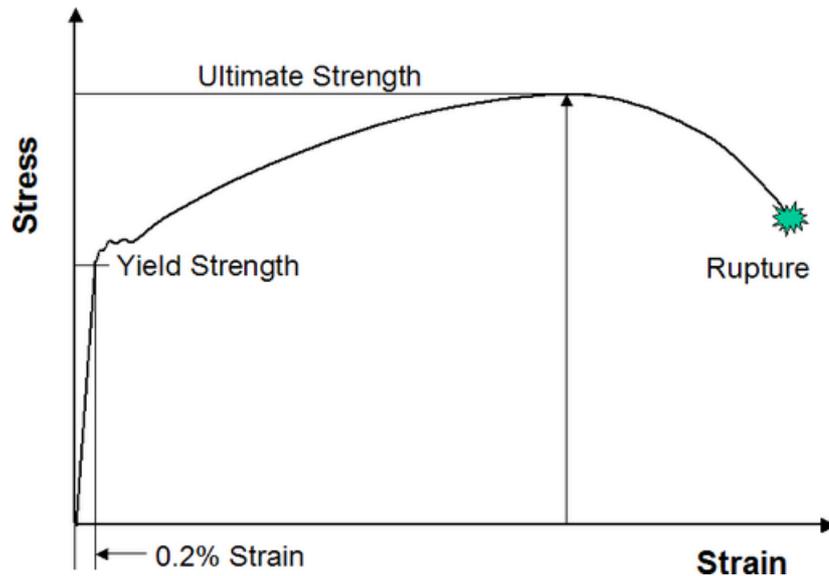
Before the optimization begins all variables and constraints are within their boundaries:



After the optimization one variable and one of the three constraints are at their respective boundaries. Disk weight is reduced from 11.6731 to 10.0204 kg in this example



### 6.3.6 Terminology



#### Tensile Strength

Tensile strength measures the force per cross sectional area required to pull a test specimen to the point where it breaks. While the stress is low, the length of the material will increase proportional to the force applied. When the force is removed, then the material will relax to its original shape. When a certain stress is exceeded, then a plastic deformation happens and the shape of the material will change permanently.

## Yield Strength

The stress a material can withstand without permanent deformation

## Ultimate Stress

The maximum stress a material can withstand

## von Mises Stress

von Mises stress is a combination of stresses in two or three dimensions which can be compared to the tensile strength of a material loaded in one dimension

$$\sigma_{vonMises} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

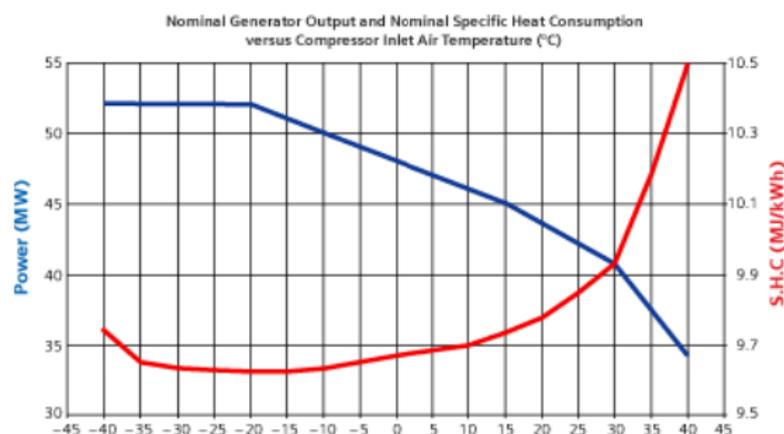
## Poisson's ratio

During a tensile test, the reduction in cross-sectional area is proportional to the increase in length in the elastic range. The ratio of transverse contraction to longitudinal extension of the material is Poisson's ratio.

## 6.4 Digitizing a Picture

### 6.4.1 The Task

You may have information in form of a picture, but you need numbers. For example, you may have got a gas turbine manufacturers brochure with performance data and you want to model the performance of this engine with GasTurb.



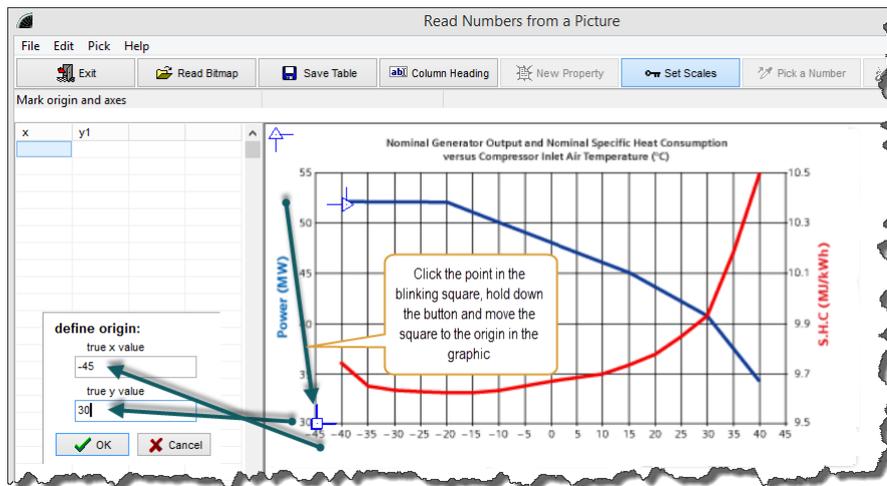
When you have these data numerically, then you can use them as **Comparative Data** that are shown in the GasTurb graphical output together with the simulation results. Another application example for this program feature would be if you have measured data only as a picture and not numerically.

With GasTurb Details 6 you can read any graphic in bitmap format, show it on your computer screen and pick the numbers from the picture with mouse button clicks.

### 6.4.2 Setting the Scales

After having selected **Read from a Picture** on the **Extras Panel** the first action is reading a graphic in bitmap format (file extension bmp). Next the scales of the graphics must be correlated with the pixel coordinates on the screen.

A blinking square and two blinking triangles appear in the top left corner of the graphic. With these symbols you must mark the axes: the square is for the origin where the y-axis crosses the x-axis. First click the point in the center of the blinking square, keep the mouse button pressed and move it to the origin of the graphic. After releasing the button, the true numbers of the graphics origin must be input in the two edit fields which appear. In the example below the true x value of the origin is -45 and the true y value is 30. Click the OK Button to proceed with one of the two blinking triangles. Place the triangle pointing to the right to the right end of the x-axis and the triangle pointing upwards to the upper end of the y-axis.



When you set the upwards pointing triangle, then the true x-value is shown in a disabled edit field; you can only input the true y value for the marked point. Similarly, when you set the true x value for the right end of the x axis, the true y value is shown in a disabled field.



After having set the origin as well as the end values for the x and y axis you can go for picking numbers from this graph.

### 6.4.3 Reading Numbers

Before commencing with picking numbers you should edit the table column headings. After that click the **Pick a Number** button. While you move the mouse pointer over the image you will see the numbers which will be transferred to the table when you click on the graphic. If you accidentally click a wrong spot then erase it by clicking the **Erase Last Point** button.



Each click fills a line in the table and produces a cross in the graphic:



Often you will have only one line in your graphic. When you are done with picking numbers from this single line then you must save them to a text file before closing the window. However, as in the example above, there might be several quantities plotted over the same x-axis. How to handle such a situation is described in the following section.

### 6.4.4 Several Lines

After having finished the number picking for the first line you can go for a second and a third line which have a common x-axis with the first line. To initiate a new line click the New Property button. You will get the opportunity to enter a headline for the next column in the table before the number picking begins.



The new property may be assigned to the same y-axis or to a different y-axis. In the latter case you must reset the y-scale which can be done after clicking the Set Scales button. Click the point in the triangle at the y-axis (without moving the mouse) and enter the new true y value for the end of this axis and similarly adapt the true y value of the origin value after clicking the point in the blue square. When the new scaling is completely defined, then you can pick numbers again. Note that you can not modify or add new x-values at this stage of the work.

---

## 7 References

[1] P. P. Walsh, P. Fletcher  
Gas Turbine Performance  
Blackwell Science Ltd, 1998

[2] J. Kurzke  
Performance modeling methodology: Efficiency definitions for cooled single and multistage turbines  
ASME paper 2002-GT-30497 presented at the Turbo Expo 2002 in Amsterdam

[3] Arthur J. Glassman  
Users Manual for Updated Computer Code for Axial Flow Compressor Conceptual Design  
NASA Contractor Report 189171, 1992

[4] Arthur J. Glassman  
Computer Program for Preliminary Design Analysis of Axial Flow Turbines  
NASA TN D-6702, 1972

[5] Sanford Gordon  
Thermodynamic and Transport Combustion Properties of Hydrocarbons With Air  
NASA TP 1906, 1982

[6] Michael T. Tong, Ian Halliwell, Louis J. Ghosn  
A Computer Code for Gas Turbine Engine Weight and Disk Life Estimation  
Journal of Engineering for Gas Turbines and Power, April 2004, Vol. 126, pp 265-270

[7] The International Association for the Properties of Water and Steam  
Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of  
Water and Steam  
August 2007

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