Experiment Instructions

ET 796 Gas Turbine Jet Engine

Experiment Instructions

Last modification by: Dipl.-Ing. J.Boxhammer

This manual must be kept by the unit.

Before operating the unit:
- Read this manual.
- All participants must be instructed on handling of the unit and, where appropriate, on the necessary safety precautions.

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1 Introduction

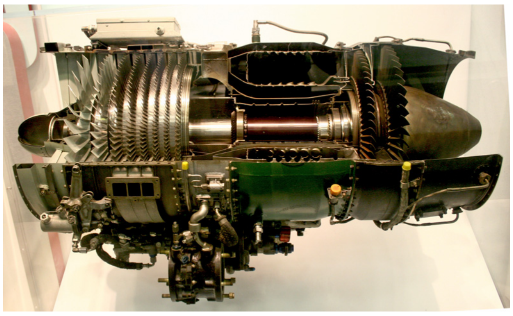


Fig. 1.1 J85-GE-17A turbojet engine from General Electric

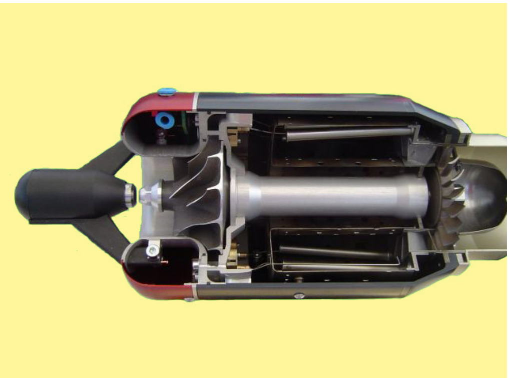


Fig. 1.2 JetCat gas turbine

The ET 796 trainer is used to demonstrate and study the function and behaviour of a gas turbine in the model scale. Gas turbine plants are used to generate mechanical and electrical energy:

- Driving generators in power plants
- Driving compressors and pumps in oil and gas extraction
- Propulsion of ships, locomotives and heavy vehicles
- For aircraft propulsion with propeller and jet engines

Gas turbines are always used where high concentration of power, low weight and quick startup are required. Unlike piston engines, being turbomachines they allow high material throughputs with small dimensions. This means lightweight yet powerful drives can be constructed.

Since the moving parts of a gas turbine only perform a rotary movement, with good balance it is possible to achieve virtually vibration-free running. The loud noise emissions caused by the high gas velocities and by contact with the atmosphere are a drawback.

Compared to steam turbines, gas turbines operate at higher temperatures but at lower pressures. The high temperatures, especially in the area of the gas turbine, require special heat-resistant materials.

The gas turbine used in the trainer is a single-shaft gas turbine. All components required for operation of the system are compactly combined in a mobile rack.

The system has a simple construction and is designed specifically for educational purposes. The operation and display of all important process parameters is summarised on a control panel.

The PC-based measurement data acquisition with evaluation software allows online logging of all relevant process variables and their graphical representation.

Besides purely demonstrating the turbine's operational behaviour, it is also possible to undertake qualitative studies such as determining the thrust and other characteristics of the gas turbine.

Learning objectives / exercises

- Operating behaviour of a jet engine including starting procedure
- Determining the specific thrust
- Determining the specific fuel consumption
- Determining the fuel-air ratio

2 Safety

2.1 Intended use

The unit is to be used only for teaching purposes.

2.2 Structure of safety instructions

The signal words DANGER, WARNING or CAUTION indicate the probability and potential severity of injury.

An additional symbol indicates the nature of the hazard or a required action.

Signal word	Explanation
⚠ DANGER	Indicates a situation which, if not avoided, **will** result in **death or serious injury**.
⚠ WARNING	Indicates a situation which, if not avoided, **may** result in **death or serious injury**.
⚠ CAUTION	Indicates a situation which, if not avoided, may result in **minor or moderately serious injury**.
NOTICE	Indicates a situation which may result in **damage to equipment**, or provides instructions on **operation of the equipment**.

Symbol	Explanation
	Electrical voltage
	Hazard area (general)
	Hot surface
	Wear ear defenders
	No naked light
	No smoking
	Oxidizing
	Flammable
	Toxic
	Notice

2.3 Safety instructions

The following instructions must be observed to ensure safe and reliable operation of the device.

All persons concerned with the device, especially students, must be familiarised with the safety instructions.

The attached operating instructions for the model gas turbine must be carefully observed. Gas turbines are delicate and sensitive machines even in the model scale. Incorrect use or careless maintenance can quickly destroy the gas turbine. Therefore the operating instructions should be studied carefully before the initial commissioning.

If any doubts arise, check with the manufacturer.

No liability can be accepted for damages resulting from incorrect use.

⚠ WARNING

Electrical connections are exposed when the control cabinet is open.

Risk of electrical shock.

- Before opening the control cabinet: Pull the plug out.
- All work must be performed by trained electricians only.
- Protect the control cabinet from moisture.

⚠ WARNING

The gas turbine housing, exhaust stack and any of the gas turbine's exhaust ducts become very hot during operation.

Risk of burns.

- Do not touch any parts
- Leave parts to cool down

⚠ WARNING

Exhaust jet is very hot (200...300°C).

Risk of burns.

- The area of the exhaust jet must be free of persons.
- Cordon off outlet area when operating as a jet engine without exhaust gas outlet routing.

⚠ WARNING

Noise emissions > 130dB(A).

Risk of hearing damage.

- Wear suitable ear defenders.

⚠ WARNING

It should always be ensured that nobody is present in the gas turbine's operating plane when the turbine is operating.

Danger area.

- Either stand in front of or behind the gas turbine, but not to the side of it.
- Comply with the following minimum safety distances for a gas turbine model.
  In front of the gas turbine: 1.0 m
  To the side of the gas turbine: 12.0 m
  Behind the gas turbine: 10.0 m

⚠ WARNING

Strong blow out force at the fan outlet. Loose objects sucked in can be ejected at high speed.

- Before switching on: Ensure that there are no loose items present in or behind the device.

⚠ WARNING

In the event of a jet fuel leakage, do not use an open flame and avoid sparks.

Risk of fire.

- Do not switch any electrical consumers on or off.
- Check the system for leaking fuel lines before use.
- Wipe up spilled jet fuel. Note that cloths soaked in jet fuel are a risk of spontaneous combustion (ventilate well).

⚠ WARNING

Do not allow any combustible materials to come into contact with the hot exhaust pipe or to get into the exhaust jet.

Risk of fire.

- A wide zone around the outlet area must be kept free of combustible or heat-sensitive materials.
- Minimum distance to combustible materials in the direction of the exhaust gas stream: 4 m

⚠ WARNING

In the event of fuel leaks in the gas turbine, jet fuel can ignite on the hot turbine housing.

Risk of fire.

- System must not be operated if fuel is leaking.

⚠ WARNING

Exhaust gases contain odourless carbon dioxide and carbon monoxide. There is a risk of suffocation or poisoning.

Carbon dioxide can suffocate and carbon monoxide can poison.

- Never operate the gas turbine without an exhaust pipe.
- The exhaust pipe must lead outside under all circumstances.
- Ensure adequate ventilation.

⚠ WARNING

Smoking or open flames when handling combustible fuels can lead to explosion or deflagration.

Possibility of severe injuries.

- No open flame
- No smoking
- Erect warning sign
- Comply with relevant statutory provisions when transporting and storing fuels (kerosene, petroleum, etc.).

⚠ WARNING

Fire hazard due to overheating of the gas turbine.

The strong suction effect at the air inlet can cause loose objects such as paper, cleaning cloths or parts of clothing to be caught up by the air flow to the air inlet opening during operation. This can clog the intake screen and cause overheating and fire in the gas turbine.

- Only operate the gas turbine with the safety guard mounted.
- Do not store loose items where they can be sucked in by the gas turbine.
- Do not operate the gas turbine unattended.

⚠ WARNING

When handling fuel, drops of fuel could get into the eyes.

Risk of injury to the eyes.

- Wear safety goggles

If fuel gets into the eyes:

- Rinse eyes immediately
- Seek immediate medical attention

NOTICE

Gas turbine must not draw in foreign bodies or dust.
Dust is deposited in the turbine bearings and destroys them. The intake area must be kept free of loose objects.

NOTICE

A suitable fire extinguisher must be kept near the unit during operation.

NOTICE

The system may not be operated unattended.

NOTICE

Only operate gas turbine with a mixture of turbine oil and pure kerosene or petroleum. Unsuitable fuel may cause overheating or residue formation.

NOTICE

Fuel must be mixed with turbine oil to lubricate the turbine bearings.
Only use suitable synthetic oils as specified in the appendix.

NOTICE

The gas turbine must be overhauled every 50 operating hours. This work must be carried out by the gas turbine manufacturer JET-CAT.

NOTICE

If critical operating conditions (overspeed, excess temperature, leaks, etc.) occur, always switch the operating mode switch to "off" before doing anything else.

NOTICE

The system is not suitable for outdoor use. The system must be operated in dry, dust-free and well ventilated rooms. In particular, good ventilation must be ensured, since the system requires over 800 m^3/h of air.

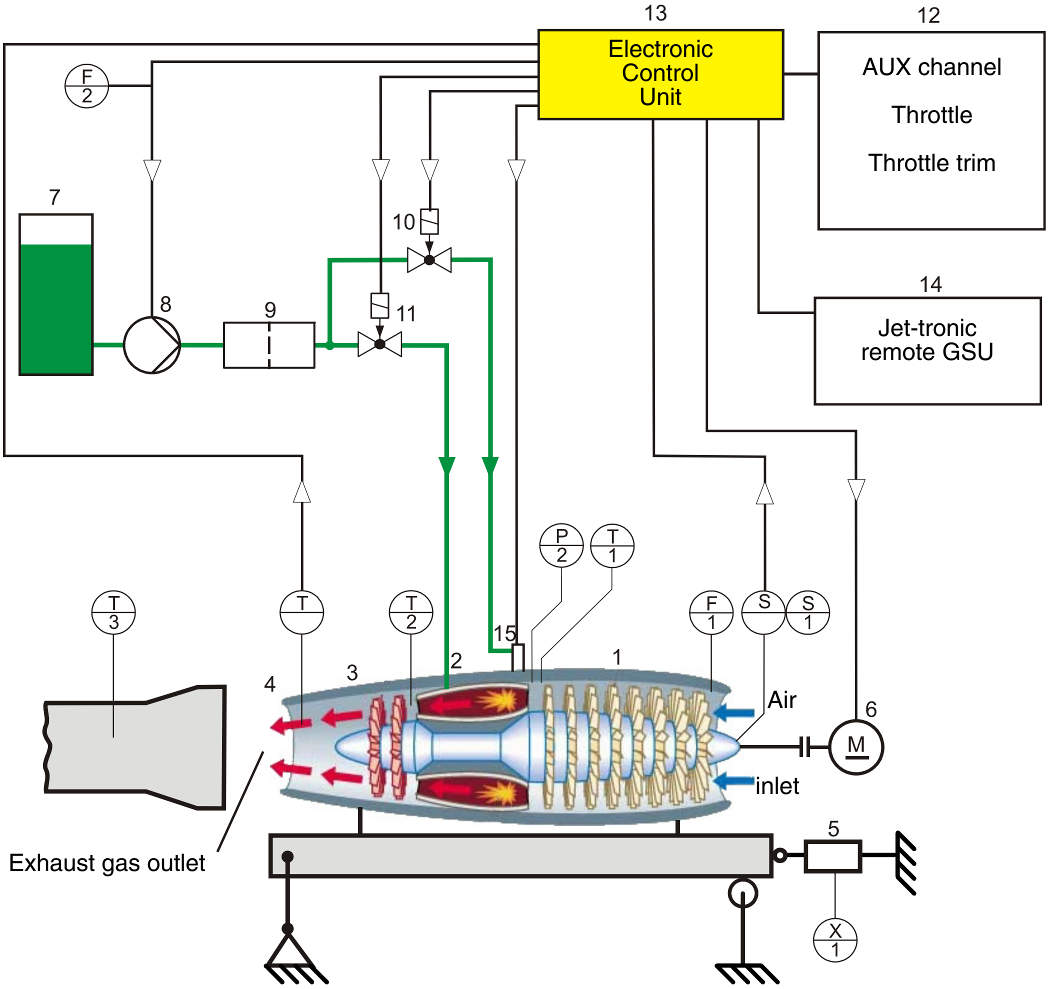
NOTICE

The gas turbine is designed to be electrically insulated on the thrust measuring table. There is a potential of +12 V at the gas turbine housing. It is important to ensure that no electrically conductive connection between the gas turbine and table is established.

2.4 Ambient conditions for the operating and storage location

- Enclosed space
- Free from dirt and humidity
- Level and fixed surface

3 Description of the device



1	Compressor	13	Electronic control unit
2	Combustion chamber	14	GSU
3	Turbine	15	Glow plug
4	Jet nozzle		
5	Thrust force sensor	X1	Thrust
6	Starter motor	P1	Combustion chamber pressure
7	Fuel tank	F1	Air volumetric flow rate
8	Fuel pump	F2	Fuel consumption
9	Fuel filter	S1	Speed
10	Fuel solenoid valve for start	T1	Compressor temperature
11	Fuel solenoid valve	T2	Combustion chamber temperature
12	Operating unit	T3	Gas turbine outlet temperature

Fig. 3.1 View of the information panel

The trainer includes a complete gas turbine system with the following sub-systems:

- **Model gas turbine** consisting of compressor (1), combustion chamber (2), turbine (3) and jet nozzle (4) with means for thrust measurement (5).
- **Fuel system** consisting of fuel tank (7), fuel pump (8), fuel filter (9), fuel solenoid valve (11) and electronic control unit (13).
- **Starter and ignition system** with starter motor (6), fuel solenoid valve for start (10) and glow plug (15).
- **Measurement and control instrumentation** with temperature, flow rate, speed and pressure measuring points and associated displays. This also includes safety elements such as temperature and speed limiters.

3.1 Design of the trainer

All parts of the system are arranged on a table frame. The fuel tank, pump with filter, solenoid valve for start and the fuel solenoid valve for fuel supply are located below the table top. The power supply, the measurement data acquisition with displays and the gas turbine control system are all located in the control cabinet.

3.2 Device design

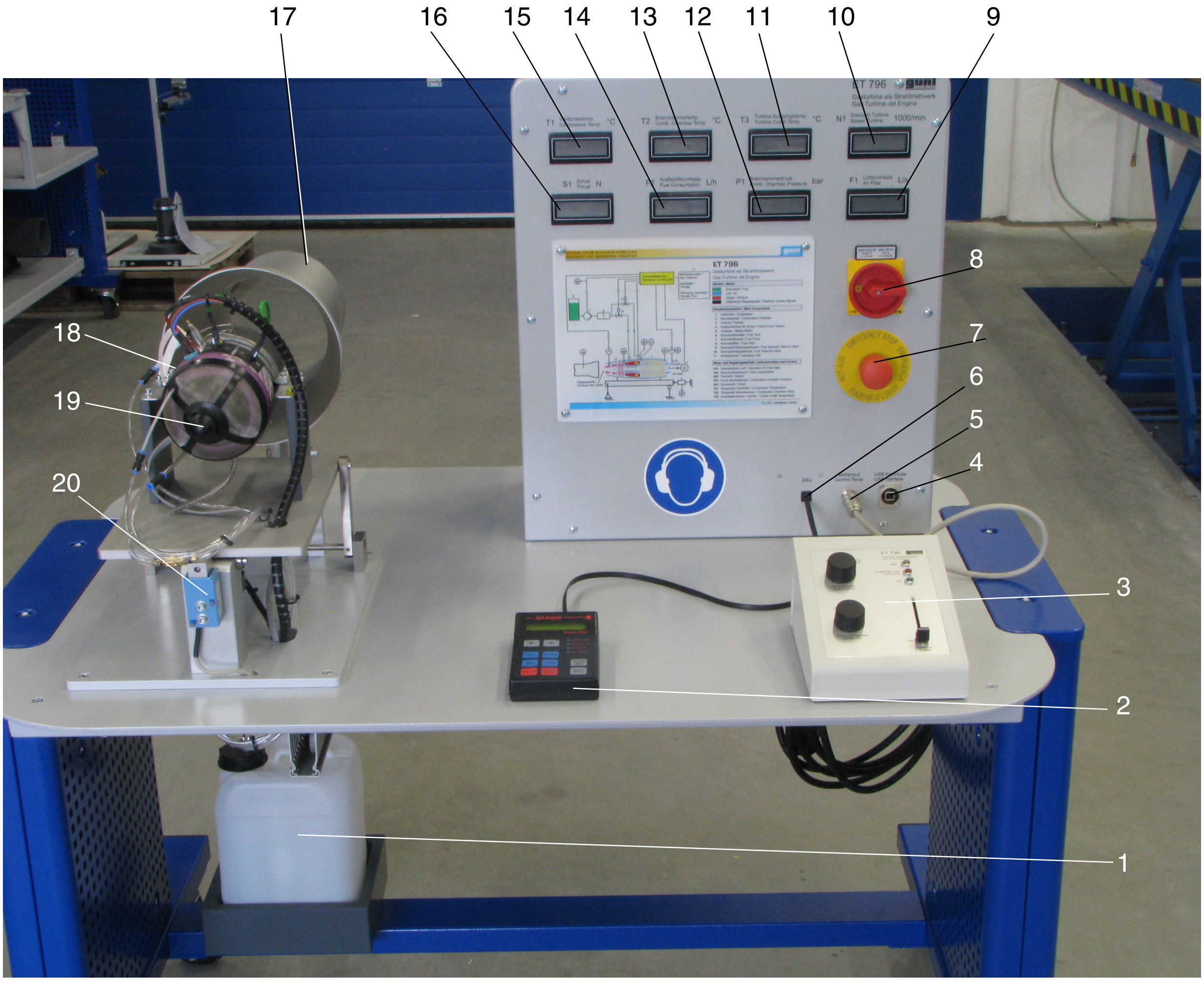


Fig. 3.2 Front view

1	Fuel tank	11	Gas turbine outlet temperature T3
2	GSU (Ground Support Unit)	12	Combustion chamber pressure P1
3	Operating unit	13	Combustion chamber temperature T2
4	USB connector for the PC	14	Fuel consumption F2
5	Connection for the operating unit	15	Compressor temperature T1
6	Connection for the GSU	16	Thrust X1
7	Emergency off switch	17	Mixing tube
8	Main switch	18	Gas turbine
9	Air volumetric flow rate F1	19	Air inlet with safety guard and starter motor
10	Turbine speed S1	20	Thrust force sensor

3.3 Process schematic

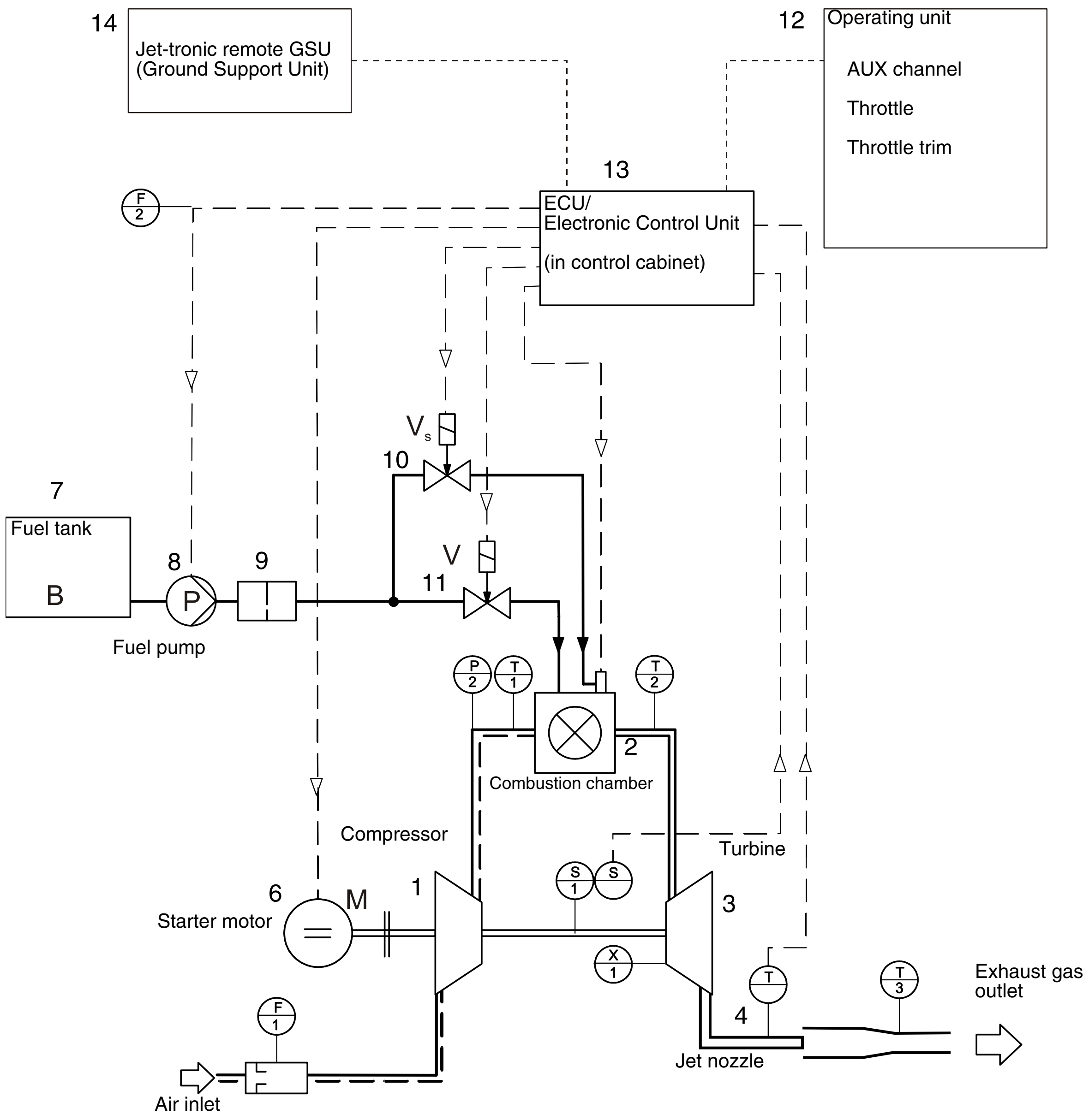


Fig. 3.3 Process schematic for the gas turbine (see page 13 for part numbers)

3.4 Components of the trainer

3.4.1 Gas turbine

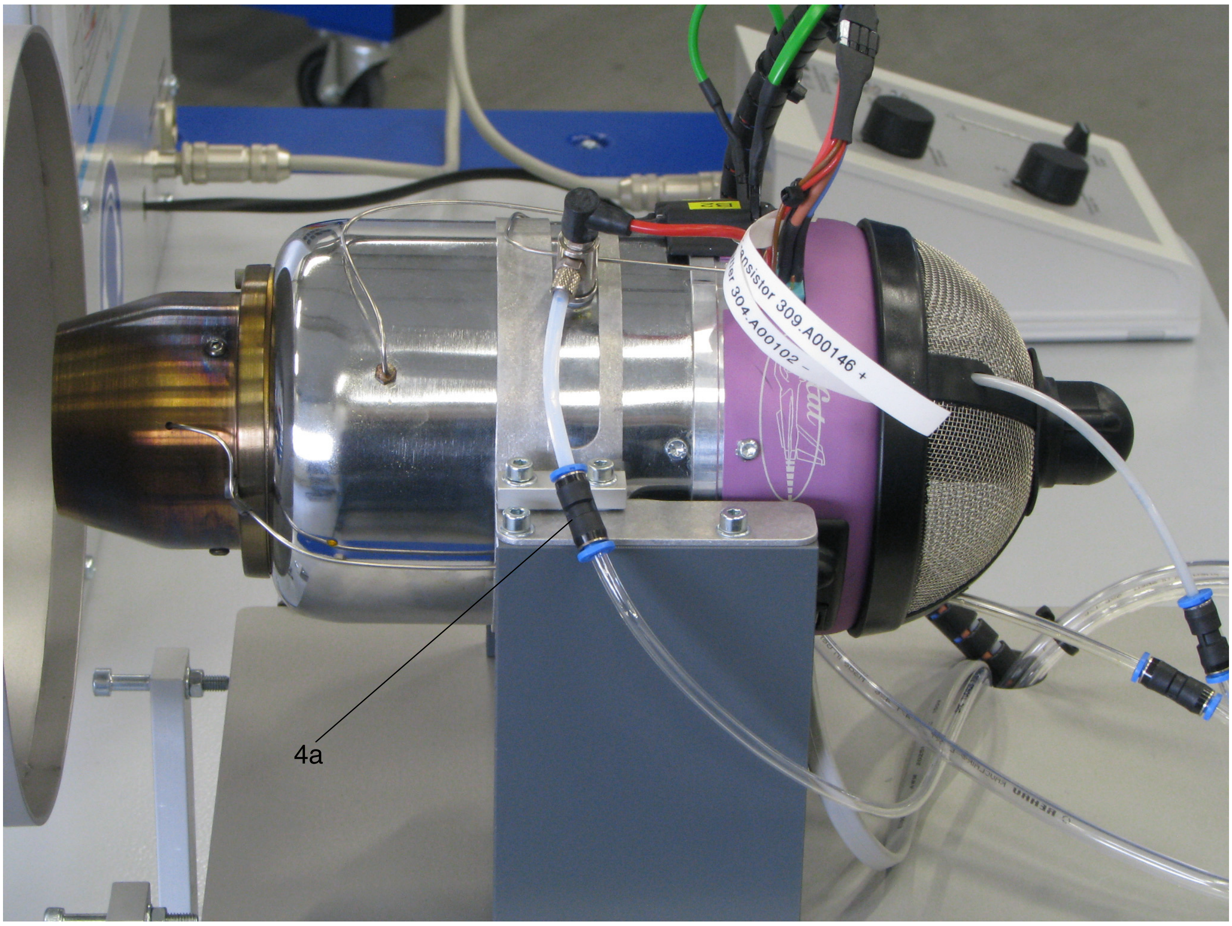


Fig. 3.4 Gas turbine P80-SE

The model gas turbine forms the core of the system. It consists of an axial turbine with direct-coupled radial compressor and an annular combustion chamber. The turbine and compressor form a compact unit with the bearing housing positioned between them. This gas turbine was originally used to power model aeroplanes. The air drawn in is accelerated into the light metal diffuser housing (2) by the rapidly rotating impeller

(1) (35000...115000 min^{-1}). Here, the velocity of the air is converted into pressure.

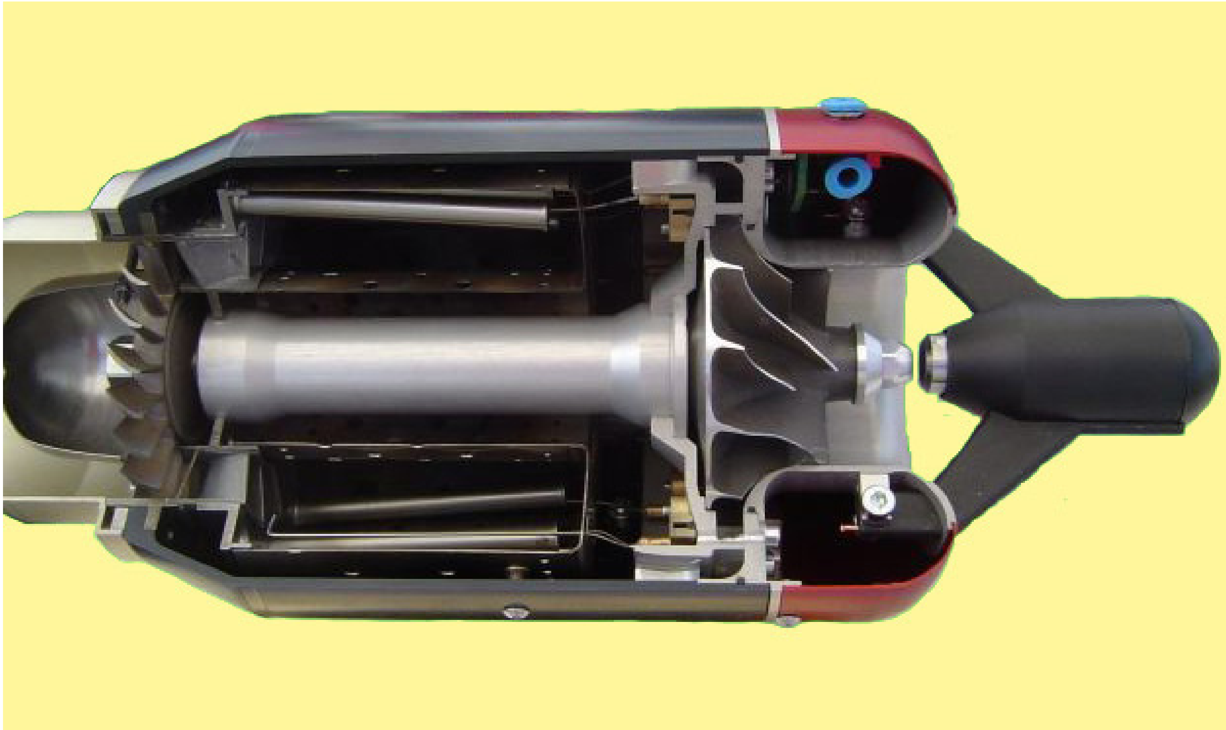


Fig. 3.5 Section model of a JetCat gas turbine

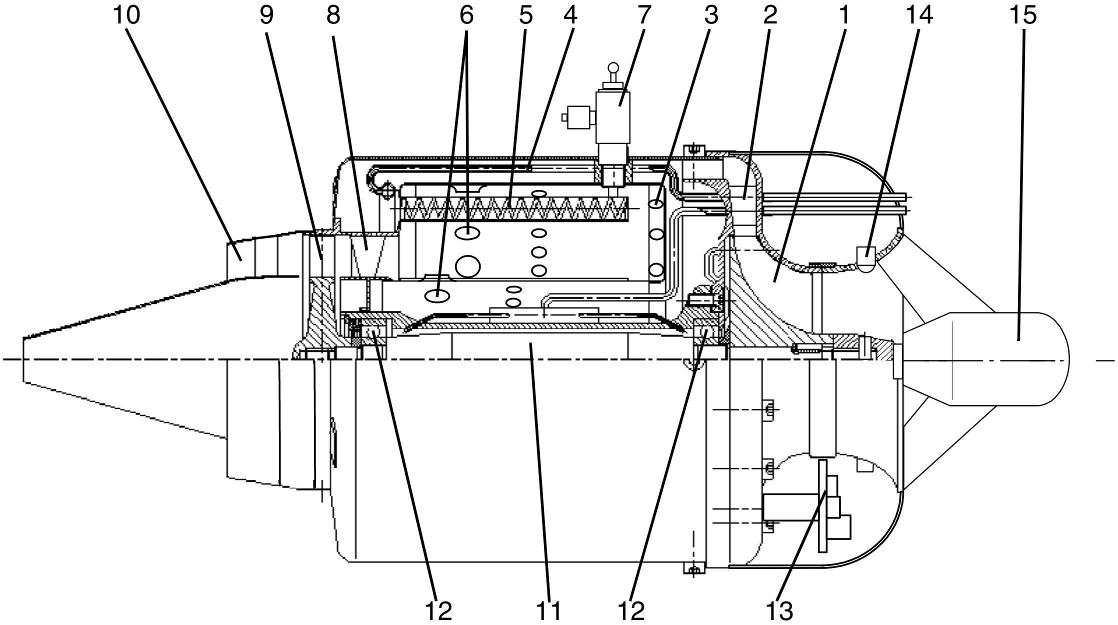


Fig. 3.6 Model gas turbine

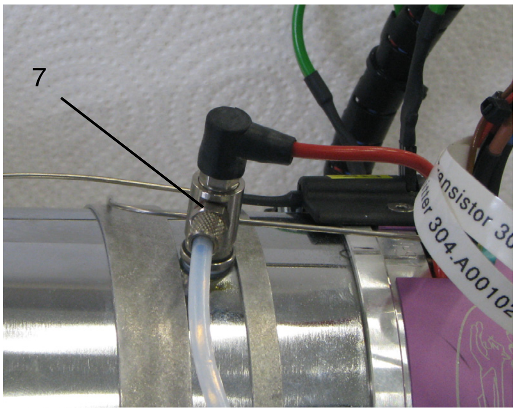


Fig. 3.7 Turbine glow plug with fuel line (white) and electrical connection (red)

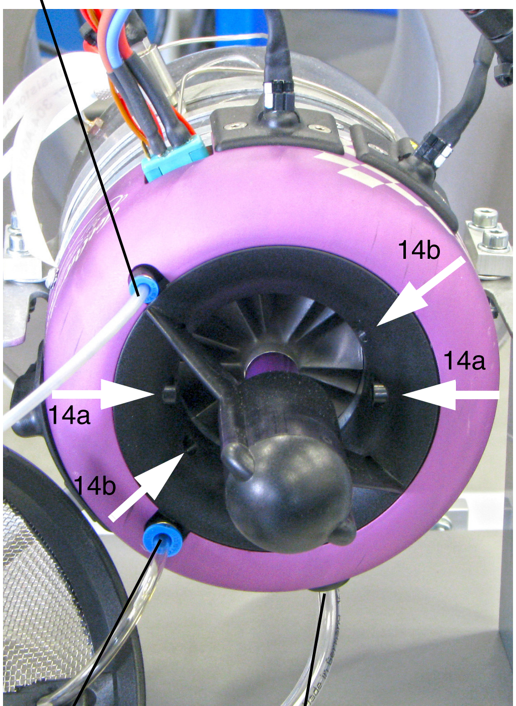


Fig. 3.8 Intake nozzle with measurement holes for measuring the speed

A portion of the air is branched off at the entrance to the combustion chamber (3) and fed to the flame tube (4) at the end. The liquid fuel enters the evaporator pipes (5) from the rear. Here the fuel is evaporated and mixed with the primary air and combusted in the front part of the combustion chamber. The secondary air cools the flame tube from the outside. This is fed to the flame tube through holes (6) in order to cool the extremely hot combustion gases (about 2000°C) to the permissible inlet temperature of 600...800°C.

A glow plug (7) fed by start fuel is used for ignition at startup. From the combustion chamber, the combustion gases flow into the turbine guide vanes (8) and are accelerated to enter into the axial impeller (9). In the impeller, the gases emit some of their energy to the impeller in order to drive the compressor. The gases are partially expanded and cooled. They leave the jet nozzle at about 600°C.

Turbine and compressor impeller are mounted overhung on a shared shaft (11). The shaft is guided in ball bearings (12) in the bearing housing. The bearings are cooled by the compressor air and lubricated by a mist of fuel and turbine oil.

The electronics (13) for the starter motor (15), temperature monitoring and speed measurement (14, 14a, 14b) are housed under the front hood.

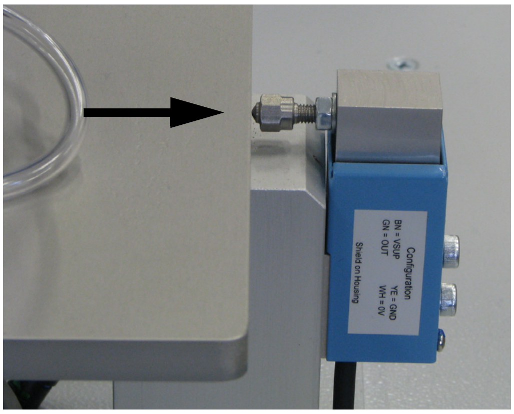
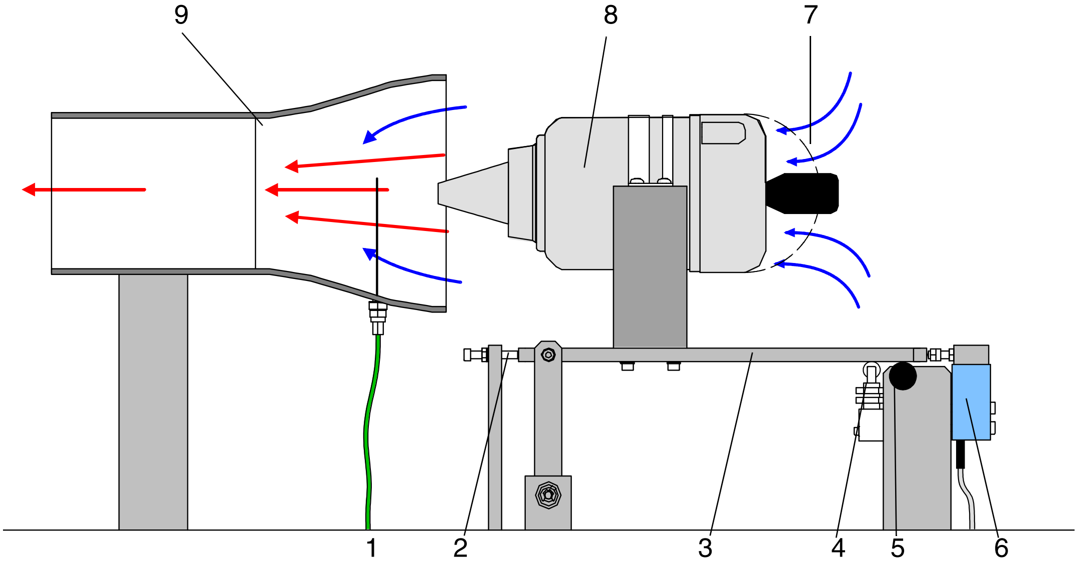


Fig. 3.9 Thrust table with force sensor

The exhaust jet draws in additional secondary air through the injector effect. This mixes with the exhaust jet in the mixing tube (Fig. 3.10-9) and decreases the outlet temperature.

The entire gas turbine with the thrust table (Fig. 3.10-3) is mobile (Fig. 3.10-5), so that the thrust of the gas turbine can be measured via a force sensor (Fig. 3.9, Fig. 3.10-6).

The quantity of drawn-in air is measured directly at the air inlet using the intake nozzle below the air inlet (7).



1	Temperature sensor T3
2	Limit screw for the thrust table
3	Movable thrust table
4	Safety limit switch
5	Roller for storage
6	Force sensor
7	Air inlet into the gas turbine
8	Gas turbine
9	Mixing tube as exhaust pipe

Fig. 3.10 Gas turbine with mixing tube and force measuring device

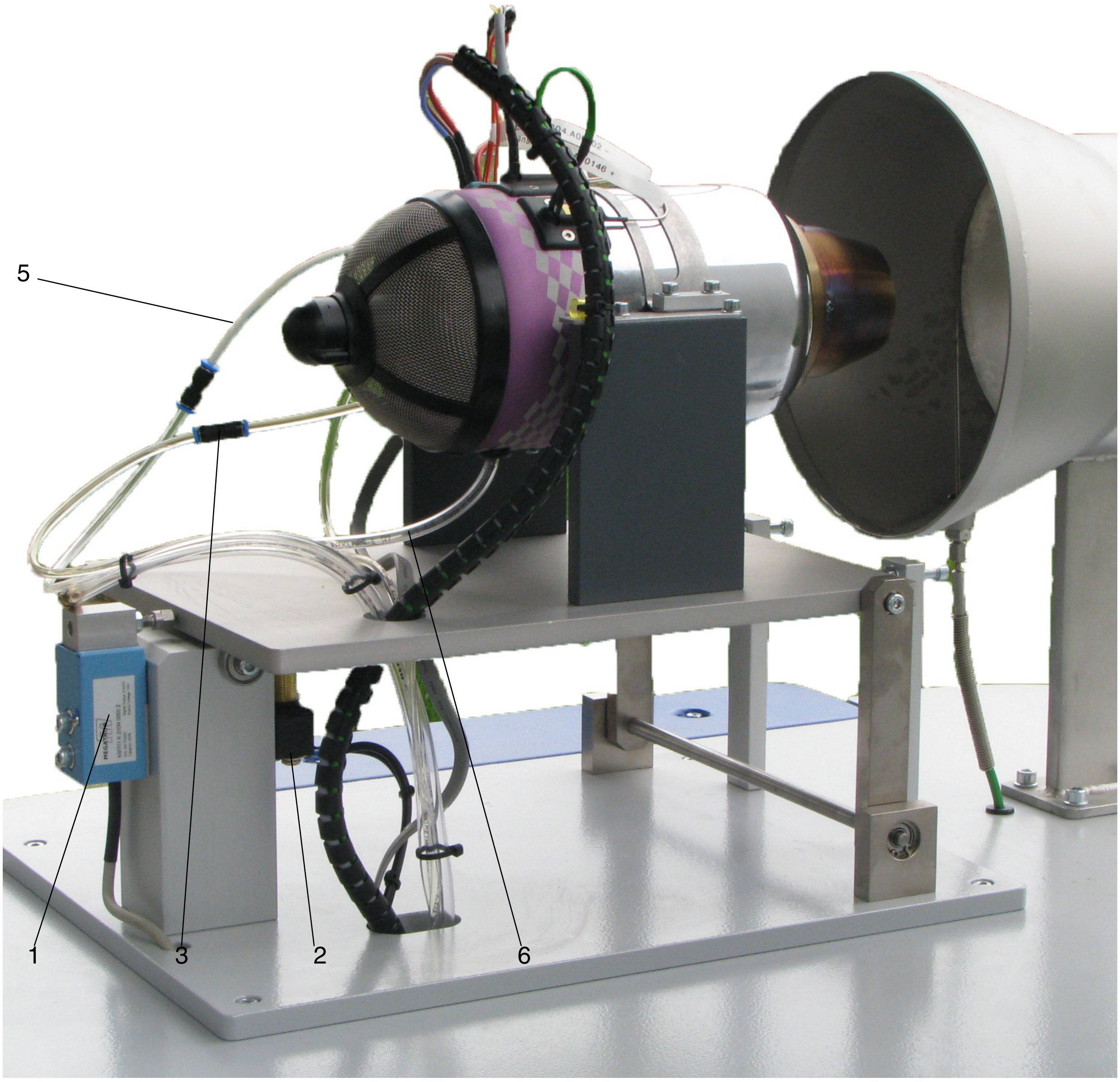


Fig. 3.11 Gas turbine on the movably mounted thrust table

1 - Force sensor
2 - Safety limit switch
3 - Hose coupling for venting the main fuel line
4a - (see Fig. 3.4) Hose coupling for bleeding the start fuel line
5 - Combustion chamber pressure measuring line
6 - Inlet nozzle measuring line for measuring the intake air

3.4.2 Fuel system

Fig. 3.12 Fuel tank - fuel solenoid valve and pump are located under the table

Kerosene or petroleum are used as fuel. Some turbine oil is mixed into the fuel to lubricate the turbine bearing (ratio of 1:20). The turbine has a low pressure system with an evaporator. An electric fuel pump pumps the fuel into the turbine's evaporator tubes. The speed of the pump and thus the amount of fuel is controlled and monitored by the electronic control unit (ECU).

A fuel solenoid valve prevents the flow of fuel in an emergency. When starting up the gas turbine, combustion is initiated via a separate start fuel line and a glow plug.

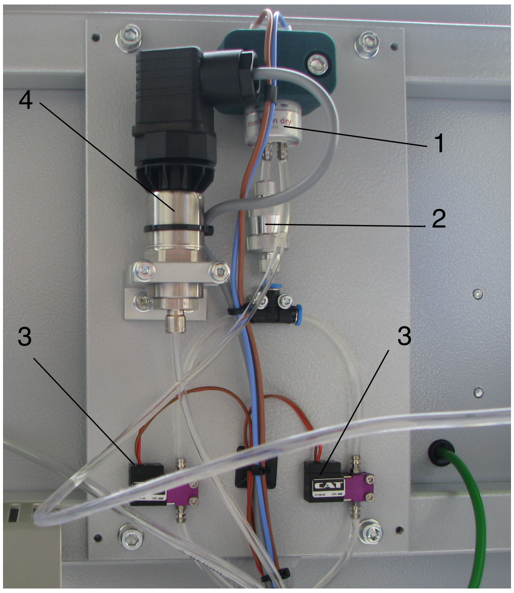


Fig. 3.13 View under the table, under the cover
1 - Fuel pump
2 - Fuel filter
3 - Fuel valves (start and main valve)
4 - Combustion chamber pressure sensor P1

3.4.3 Starting and ignition system

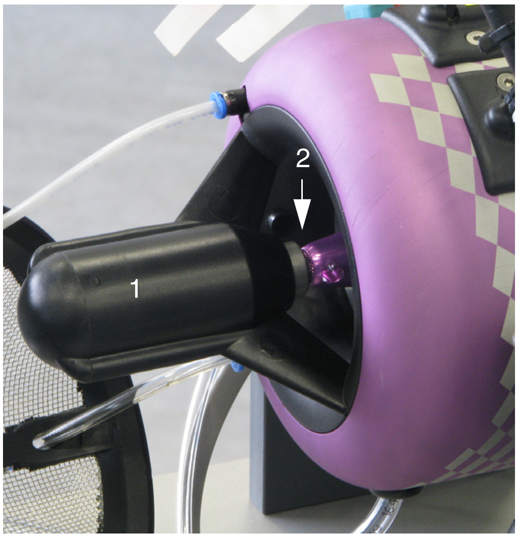


Fig. 3.14 DC motor (1) in the disengaged state (2)

The automatic starting system consists of a powerful DC motor. This drives the compressor impeller via an automatic cone clutch. At a certain minimum speed of approximately 3000 min^{-1}, the glow plug is turned on and the start fuel supplied via a solenoid valve. The start fuel evaporates at the glow plug and ignites. After successful ignition, the electric motor accelerates the turbine. At a certain speed of approximately 5000 min^{-1}, the main fuel supply is switched on and the start fuel supply switched off. Once the sustaining speed has been reached, the starter motor is automatically disengaged. The entire startup process is monitored by speed and turbine temperature and controlled electronically.

3.4.4 Control elements

All indicators and connectors, as well as the main switch and emergency stop switch are located on the control cabinet. The USB connector, the connector for the operating unit and the connector for the "Jet-tronic remote GSU" (Ground Support Unit) display and programming unit are all located in the lower part.

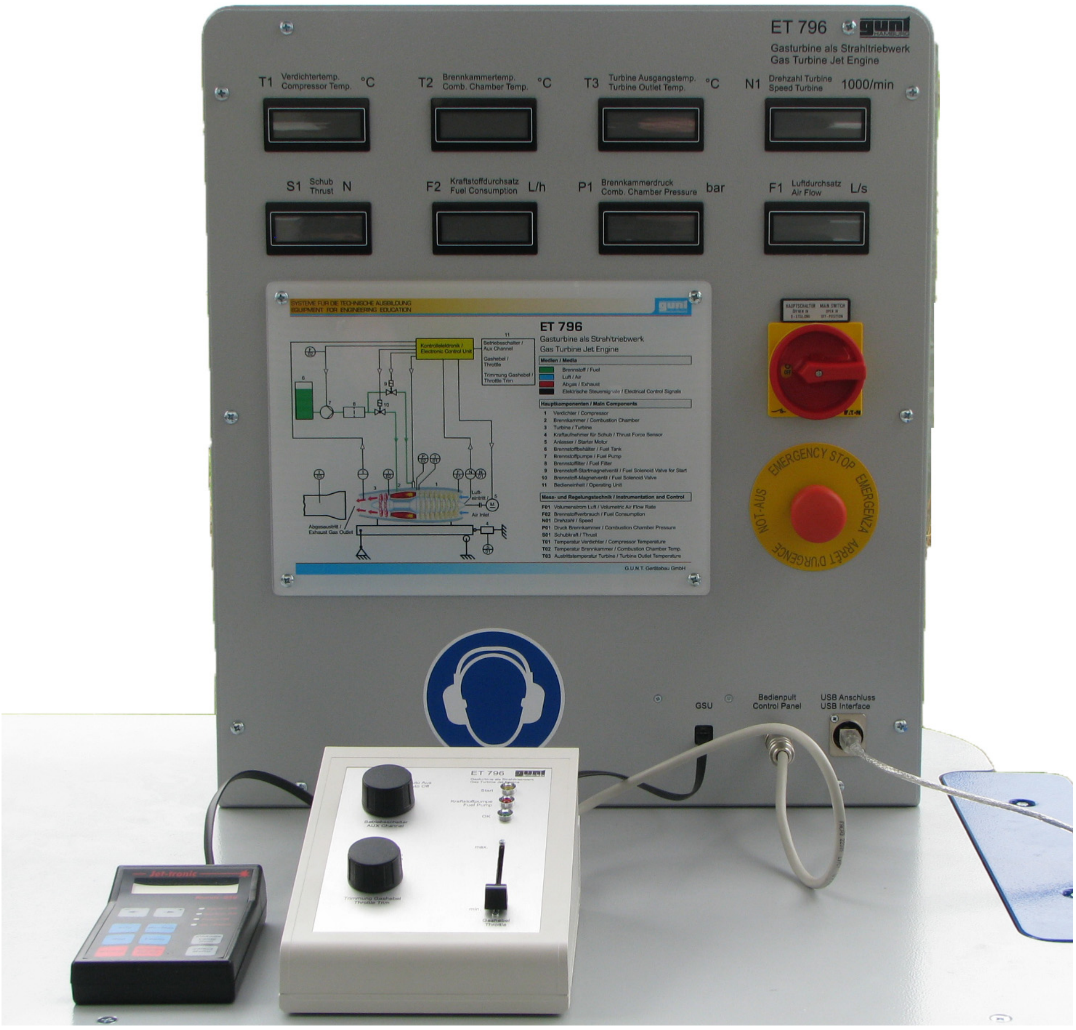


Fig. 3.15 Displays and controls on the control cabinet

The gas turbine is operated via the gas turbine's operating unit. This houses the electronic control unit's status indicators (1) and the controls required for operation. The Throttle slider is used to set the gas turbine's power output. The gas turbine can be turned off using the Throttle Trim switch. The gas turbine is switched on and off using the AUX Channel switch.

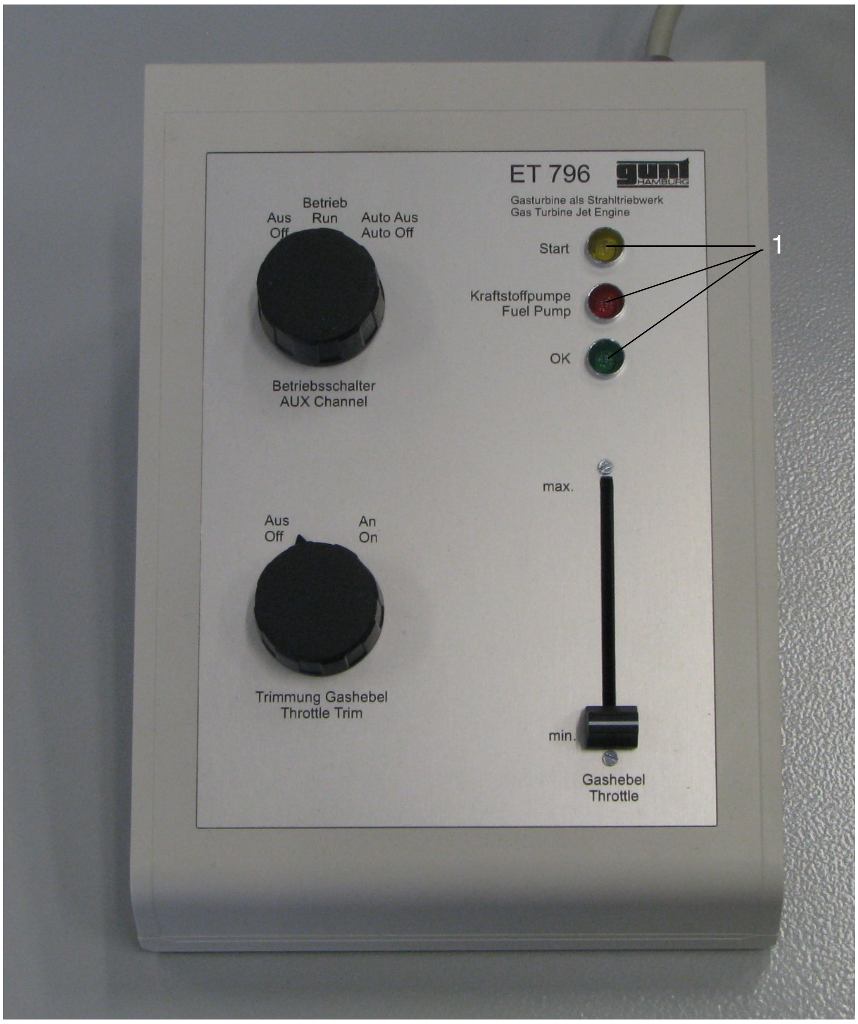


Fig. 3.16 The gas turbine's operating unit

Connecting the (Jet-tronic) display and programming unit provides additional useful information about the status of the gas turbine via the "Jet-tronic remote GSU" display. Connecting the Jet-tronic is not essential for operation of the gas turbine.

Fig. 3.17 Jet-tronic remote GSU (Ground Support Unit)

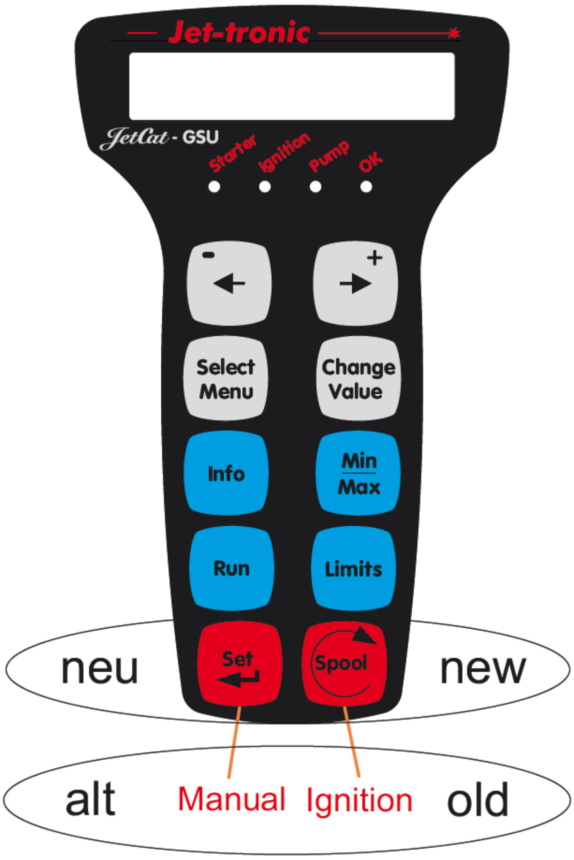


Fig. 3.18 Jet-tronic GSU from 01/09/2014

3.5 Measurement data acquisition

3.5.1 Program installation

Required for installation:

- A ready-to-use PC with USB port (for minimum requirements see Chapter 6.1).
- G.U.N.T. CD-ROM

  All components required to install and operate the program are included on the CD-ROM provided by GUNT.

Installation procedure

NOTICE

The trainer must not be connected to the PC's USB port while the program is being installed. The trainer may only be connected after the software has been successfully installed.

- Start the PC.
- Insert the G.U.N.T. CD-ROM.
- In the "Installer" folder, launch the "**Setup.exe**" installation program.
- Follow the installation procedure on screen.
- Installation will run automatically after starting it. The following program components are installed onto the PC:
  - Program for PC-based data acquisition.
  - Driver routines for the "LabJack®" USB converter.

- When the installation program has finished: Restart the PC.

3.5.2 Program operation

- Select the program and run it via:
  Start / Programs / G.U.N.T. / ET 796
- When you start the software for the first time after installation you are prompted to select the desired language for the program operation.

  The language may be changed at any time in the "**Language**" menu.
- Various pull-down menus are available for other functions.
- For detailed instructions on use of the program refer to its Help function. You can get to the **help function** via the **"?"** pull-down menu and selecting **"Help"**.

Fig. 3.19 Language selection

Saved measurement data can be imported into a spreadsheet program (e.g. Microsoft Excel) for further processing.

3.6 Setting up the gas turbine

3.6.1 Checking the gas turbine

Before the gas turbine is operated for the first time, it must be checked for transport damage and misalignment.

If training or initial commissioning was also ordered through G.U.N.T., then this check is carried out by G.U.N.T. employees.

– Check all screws for tightness.

– Check all hoses for tightness.

– Check all cables for chafe points and tightness.

The power cable and hoses directly to the gas turbine are particularly important. Loose parts can be sucked in during operation and cause severe damage to the gas turbine.

– Check the ease of movement of the turbine rotor. The rotor must rotate freely without resistance and freely spin down after being blown with compressed air.

If the rotor gives the impression of being stiff, this could be caused by a foreign body in the compressor.

3.6.2 Installation

Due to the high requirement for fresh air (approx. 800 m^3/h) the gas turbine may only be operated in large, well-ventilated spaces. Lead the exhaust gases directly to the outside or connect an exhaust line. Avoid having an exhaust line longer than 3 m due to high pressure losses. The exhaust line should be sized so that no back pressure can occur. Operation in spaces with large openings to the outside is recommended, so that the exhaust gas can be blown into the open.

- A compressed air connection to blow through the gas turbine is advisable.
- Due to the high sound level of the gas turbine (>130 dB(A)) special sound insulation measures may be required.
- Secure the model from rolling away by engaging the roller brakes.
- To ensure access for maintenance and servicing, there should be clearance of at least 1 m around the trainer.
- If an exhaust line is used, this should have a diameter of at least Ø300 mm. The exhaust line must be heat-resistant. Exhaust gases have a temperature of up to 300°C. If there is a risk of contact, the exhaust line must be protected by safety guards accordingly. If heat radiation is not desired, the exhaust line must be insulated to be heat resistant. The exhaust line must not be allowed to come into contact with combustible material. Do not use plastic brackets and seals.
- It is also possible to work without an exhaust line in open, well-ventilated halls with high ceil-

ings. In this case, it is essential that there are no combustible materials in the region of the exhaust jet.

- A licensed and certified fire extinguisher must be placed near to the gas turbine.
- Connect the electrical power supply. Plug the USB cable provided for computer-based measurement data acquisition in to the ET 796 device and connect to the PC. See installation instructions relating to the installation of hardware and software.

3.7 Operating the gas turbine

3.7.1 Preparations for start

The following tasks must be performed before starting the gas turbine:

– Check fuel level. If topping up the fuel level, make sure the appropriate turbine oil is added (see Page 69).

– Only use the highest purity kerosene or petroleum as fuel. Using poor quality fuel leads to deposits forming in the turbine's evaporator system, which in turn lead to malfunctions in the combustion chamber.

– Only use fully synthetic oil as lubricant (see Page 69)

– Connect the "Jet-tronic remote GSU" (Ground Support Unit) on the control cabinet to the ECU (Electronic Control Unit).

– Connect the operating unit on the control cabinet and adjust as follows:

  - Throttle: down
  - Throttle trim: Off
  - AUX Channel: Off

– Switch on the main switch.

– Bleed the fuel line. For trouble-free operation, make sure that there is no air in the fuel line (see Chapter 3.7.2, Page 33).

– Check the operation of the indicators.

– The gas turbine is now ready for operation.

3.7.2 Bleeding the fuel lines with the kerosene start system

Before the first start and whenever the kerosene lines are empty or contain air bubbles (e.g. fuel tank empty during operation), the system must be bled.

3.7.2.1 Switch ECU to 6V kerosene start mode.

(Already set by default)

- Switch off the main switch.
- If not already done, connect the "Jet-tronic remote GSU" to the ECU on the lower left of the control cabinet.
- Simultaneously press and hold the "Ignition" or "Spool" and "Min/Max" on the "Jet-tronic remote GSU".
- Switch on the main switch. (Keep the buttons pressed!)
- After a short time, the Jet-tronic remote GSU display shows:
  Kerosene (6V- N)
  Start activated
- Release the buttons; the ECU is now programmed for a kerosene start.

3.7.2.2 Bleeding the fuel supply to the engine:

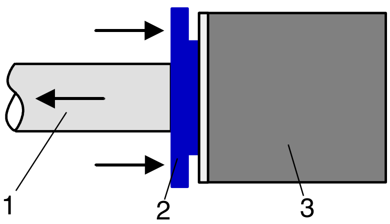


Fig. 3.20 Fuel line hose coupling
1 - Hose
2 - Blue ring
3 - Connector

1. First remove the 4 mm main fuel line (Fig. 3.11, Page 21, no. 3) from the gas turbine and lead to a collecting tank. If this isn't done, the following procedure will flood the gas turbine with fuel (-> risk of hot start).
   Loosen the fuel lines:
   Hold the blue ring on the hose coupling and pull the hose.
2. Fill the fuel tank.
3. Connect the "Jet-tronic remote GSU" on the control cabinet (ECU) and open the "Pump TestVolt" parameter in the "Test Functions" menu. (Press "Menu Select" and hold and then scroll with the +/- buttons until "Test Functions" is displayed. Now release the "Menu Select" button. Now "Purge Fuel System" appears in the display. Otherwise scroll through the Test Functions menu with the + button until the display appears.
4. Now press the "Change Value" button to start the pump (the pump power can be increased or reduced with the +/- keys while holding the "Change Value" button). Keep supplying fuel until all air bubbles are pumped out of the pipe system and fuel is coming out without any bubbles.
5. Reconnect the fuel line to the gas turbine. The main fuel system has now been bled.
   Connect the fuel lines:
   Simply insert the hose into the hose coupling and check it is firmly inserted by tugging slightly on the hose.

3.7.2.3 Bleeding the fuel supply to the kerosene start system:

1. First, bleed the fuel supply to the engine (see Chapter 3.7.2.2, Page 34). The fuel tank must be filled.
2. Disconnect glow plug connector. Failure to do so will damage the seals due to the heat.
3. Disconnect the start fuel line at the connector (see Fig. 3.4, Page 17, no. 4a) before the kerosene igniter (-> transition between fuel hose and Teflon hose) and drain into a collecting tank. If this isn't done, the following procedure will flood the gas turbine with fuel.
4. Connect the "Jet-tronic remote GSU" on the control cabinet (ECU is in the control cabinet) and open the "BurnerValve Test" parameter in the "Test Functions" menu. (Press "Menu Select" and hold and then scroll with the +/- buttons until "Test Functions" is displayed. Now release the "Menu Select" button. Then use the "+" button to scroll through the Test Functions menu until "BurnerValve Test" is displayed).
5. Now press the "Change Value" button to start the pump with low power and to supply fuel to the kerosene igniter (the pump runs at low power, the kerosene igniter valve is pulsed, the main fuel valve remains closed). Now supply fuel until all air bubbles are pumped out of the kerosene igniter's hose system and fuel is coming out without any bubbles.
6. Use the connector to re-establish the fuel connection to the kerosene igniter. Briefly supply a

bit of fuel until the Teflon hose is also filled and kerosene is present right at the kerosene igniter. The fuel supply to the kerosene start system has now been bled.

3.7.2.4 Testing and adjusting the fuel pump power

When adjusting the amount of fuel, check and adjust the hose line to the gas turbine's fuel supply, not the fuel supply to the kerosene start system.

1. First remove the 4 mm main fuel line (Fig. 3.11, Page 21, no. 3) from the gas turbine and lead to a collecting tank. If this isn't done, the following procedure will flood the gas turbine with fuel.
2. The fuel tank should be full.
3. Connect the "Jet-tronic remote GSU" to the control cabinet (ECU).
4. Press and hold the "Change Value" button. Now turn on the trainer at the main switch and release the "Change Value" button after 2 - 3 seconds. Now "Pump start volt." should appear in the GSU display.
5. Now press the "Change Value" button. The pump should run (solenoid valve for fuel supply also opens) and the current pump start-up voltage should be shown in the bottom line of the GSU display. The fuel should drip rapidly from the hose or pour out slightly. If the fuel is not running out of the hose as described, fuel pump start-up voltage must be corrected.
6. Now adjust the fuel pump start-up voltage using the +/- buttons until the fuel runs out of the fuel line as described under point 5. Check the set value from time to time by pressing the "Change Value" button. After successfully adjusting the value, save it with the "Manual" or

"Set" button. The ECU stores the value and returns to the RUN menu.

7. Reconnect the fuel line to the gas turbine.

3.7.3 Starting the gas turbine up

Gas turbines are started up in a fixed start-up procedure. This is typical of all gas turbines. Differences are only due to varying degrees of automation. In the following outline, the sequence is shown schematically over time.

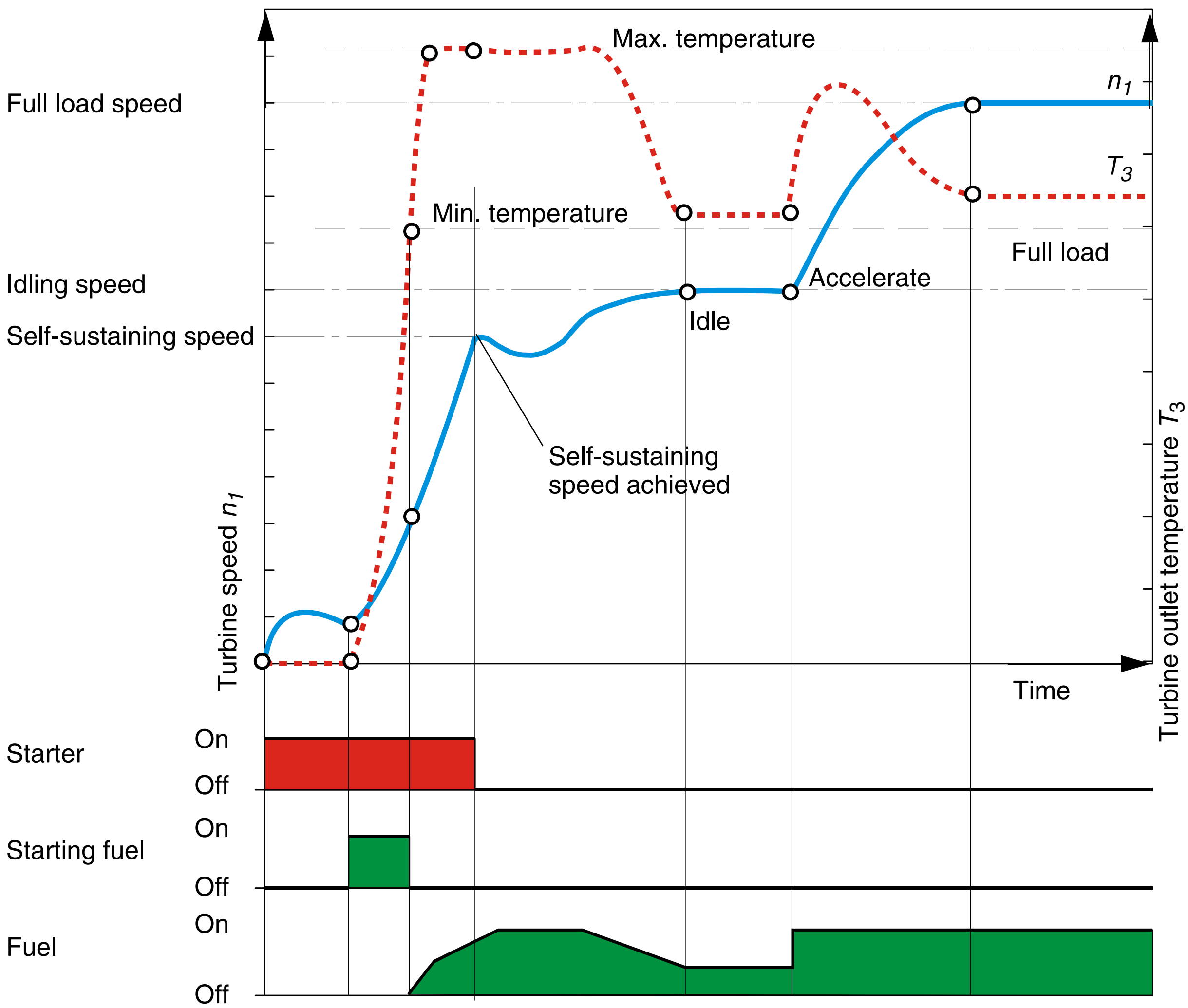


Fig. 3.21 Start-up procedure of a gas turbine

It is useful to carefully read through and memorise the description of the start-up procedure before conducting the experiments.

In the experiments, the speed and temperature curves are tracked on the gas turbine's "Jet-tronic remote GSU" display and programming unit (see JetCat gas turbine instructions).

The names of the controls refer to Chapter 3.4.4.

– To reset the gas turbine's control electronics, switch off ET 796 at the main switch.
– Check carefully whether there is still unburned fuel in the gas turbine. Unburned fuel can lead to overheating and destruction of the gas turbine as a result of uncontrolled combustion.

  If there is still fuel in the gas turbine, lift the thrust table at the front so that the fuel can run out of the back. Then blow the gas turbine dry with compressed air and carefully wipe up with a cloth.
– Switch AUX channel to "off".
– Switch Throttle Trim to "on".
– Set Throttle to idle (min).
– Switch on ET 796 at the main switch.
– Switch AUX channel to "run". The three LEDs flash in sequence.
– Start the automatic start-up process by moving the throttle to full throttle (max).

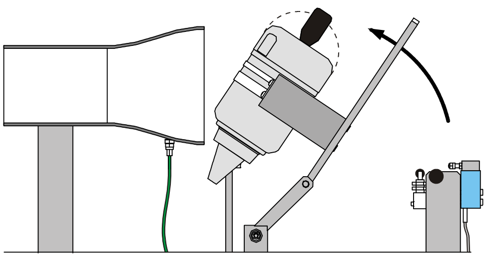


Fig. 3.22 Fold the gas turbine to remove remaining fuel

Gas turbine automatic start process

– The starter motor brings the turbine to the starting speed (yellow LED is on).

– Starting fuel is added via the glow plug, so that the gas turbine ignites. Ignition can be detected by an increase in temperature and speed.

– Main fuel valve opens (red LED on) and turbine is ramped up to approximately 50 000 min^{-1}. The temperature rises sharply.

– After a short time at 50 000 min^{-1}, the turbine is automatically slowed to the idle speed of 35 000 min^{-1}. The throttle must be returned to neutral. The green LED indicates readiness for operation.

– The thrust of the gas turbine can now be adjusted via the throttle.

3.7.4 Operating the gas turbine

NOTICE
The gas turbine may not be operated unattended. From time to time, the indicators for speeds and turbine outlet temperature must be checked.

- Speed and turbine outlet temperature are automatically monitored by the electronic control unit.

The idle speed is 35 000 min^{-1}. The full load speed should not exceed 120 000 min^{-1}.

3.7.5 Shutting down the gas turbine

The gas turbine is shut down via the gas turbine's AUX channel.

– Regular shutdown via the "Auto off" position. The turbine runs at 50 000...60 000 min^{-1} for a short period. Then the fuel pump is shut off, the combustion chamber extinguished and the turbine stops. To cool the turbine bearing, the starter motor continues to run until a temperature of less than 100°C is reached. The green LED flashes during this time.

– In an emergency, the gas turbine can also be switched off via the AUX channel "Off" position.

– After cooling down the gas turbine, move AUX channel to "Off".

For more information, see the instruction manual from the gas turbine manufacturer.

3.8 Maintenance

3.8.1 Glow plug

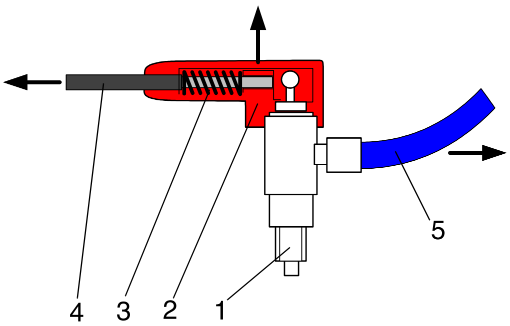


Fig. 3.23 Glow plug connector
1 - plug
2 - rubber connector
3 - spring
4 - cable
5 - fuel line

If there are problems starting up, check the glow plug for damage, short circuit or dirt. A burnt-out glow plug is detected and displayed by the electronic control unit. Replacing or loosening the glow plug:

- Hold rubber connector and gently pull on the cable to retract the spring in the rubber plug. Then remove the rubber connector from the glow plug.
- Disconnect the fuel line and unscrew the glow plug by hand.
- Screw in the new glow plug and tighten by hand.

NOTICE
Do not use a spanner. The thread of the glow plug socket may be damaged.

- Replace fuel line and rubber connector.

3.8.2 Servicing the gas turbine

The manufacturer recommends servicing the gas turbine after 50 hours of operation. The turbine bearings are replaced during this service.

Manufacturer of gas turbine model:

JetCat P80

Ing.Büro CAT M.Zipperer GmbH

Etzenberg 16

D-79129 Staufen, Germany

Tel.: +49 (0)7636-78030

Fax.: +49 (0)7636-7208

Website: www.cat-ing.de

3.9 Faults and troubleshooting

This section describes any problems that may occur with the system and their causes.

Gas turbine specific faults and the meaning of the error messages can be found in the gas turbine manufacturer's manual.

NOTICE

Unburned fuel may still be in the gas turbine after an interrupted start-up. This may combust in an uncontrolled manner when the system is restarted and damage the turbine due to overheating.

- Therefore when restarting after an interrupted start, it must be ensured that there is no unburned fuel in the gas turbine. Lift the thrust table and gas turbine at the front so that the fuel can run out of the back. The gas turbine should then be blown with compressed air to remove the remaining fuel.
- Carefully wipe up the fuel with a cloth.

Gas turbine fails to start	
No reaction with the AUX channel in the "Run" position	– Main switch not turned on – No mains voltage – Conductive connection between gas turbine and table
No ignition	– Start fuel valve defective – Start fuel line not connected to glow plug – Glow plug defective
Ignition occurs, but start-up is interrupted at low speed	
Flames at start-up	– Pump injecting too much fuel
Start-up interrupted at medium speed (10 000...20 000 min^{-1}). Strong smoke emission	– No fuel
The starter motor does not reach its speed	– Clutch slipping => clean with alcohol
Operating malfunctions	
Gas turbine stops	– No fuel – AUX channel to Off or Auto off – Main switch off – Throttle trim to off – No mains voltage

3.10 Decommissioning

- Remove any fuel remaining in the gas turbine by lifting the gas turbine up.
- Switch off the power supply at the main switch.

4 Basic principles

The basic principles set out in the following make no claim to completeness. For further theoretical explanations, refer to the specialist literature.

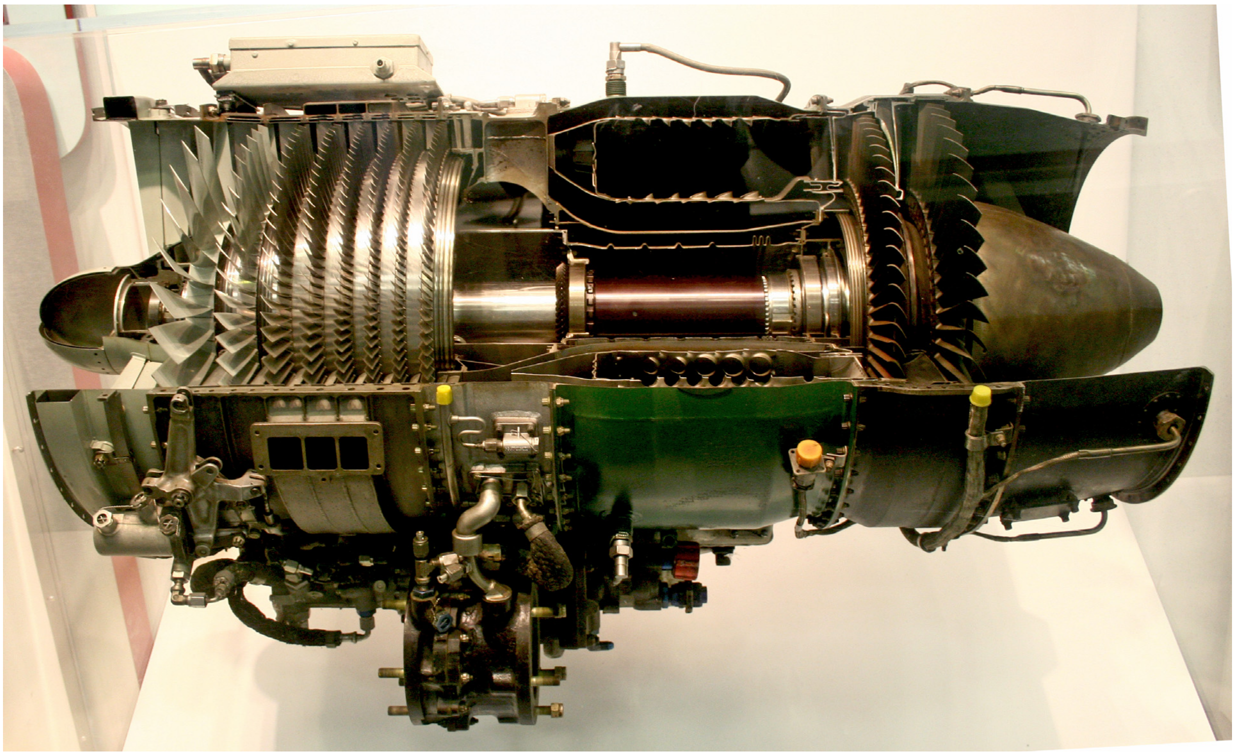


Fig. 4.1 Engine from General Electric J85-GE-17A turbojet

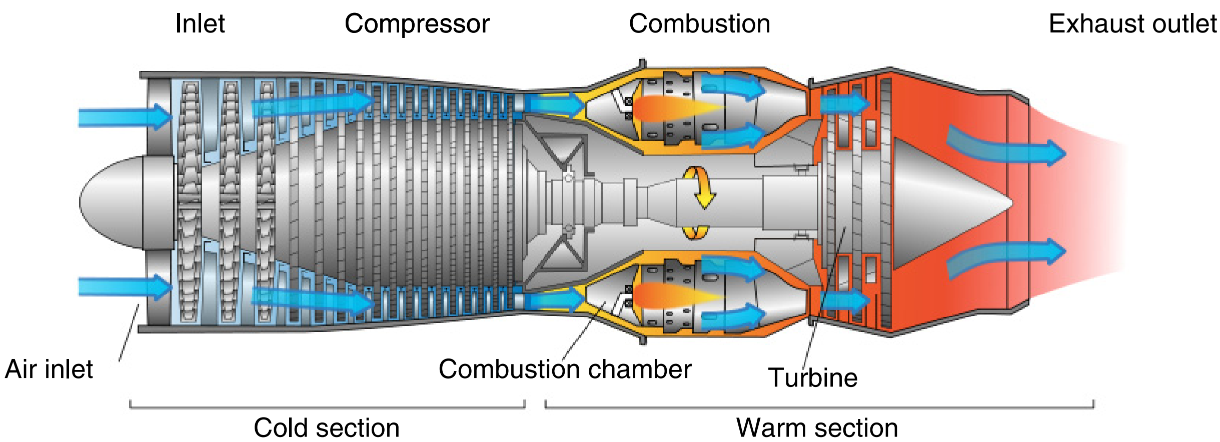


Fig. 4.2 Principle of a jet engine

4.1 The open gas turbine cycle

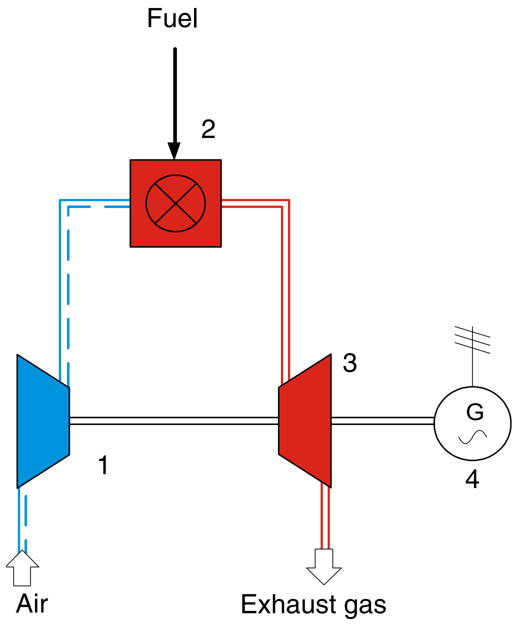


Fig. 4.3 Simple, open gas turbine

The gas turbine trainer operates according to the open thermodynamic cycle, in which the working fluid is taken from the environment and fed back to it again. In this case, the working fluid of air is subjected to the following changes of state:

- Adiabatic compression of the cold air with a compressor (1) from ambient pressure p_1 to the pressure p_2 and the associated temperature increase from T_1 to T_2.
- Isobaric heating of the air from T_2 to T_3 by supplying heat. Heat input is achieved by burning fuel with oxygen in the combustion chamber (2).
- Adiabatic expansion of the hot air in a turbine (3) from the pressure p_2 to p_1. The temperature decreases from T_3 to T_4.

In a closed thermodynamic cycle, the working medium would have to be re-cooled to the inlet temperature T_1. Even in an open cycle, the residual heat is dissipated to the environment.

The mechanical power extracted with the turbine is used in part to drive the compressor and in part to be available as useful power. Thus for example, it is possible to operate a generator (4).

4.1.1 Representation in the heat diagram

Representing the cycle in the heat chart, known as a *T-s* diagram, is useful in order to be able to better assess the conditions in the thermodynamic cycle. Here the temperature of the working fluid is plotted over the specific entropy.

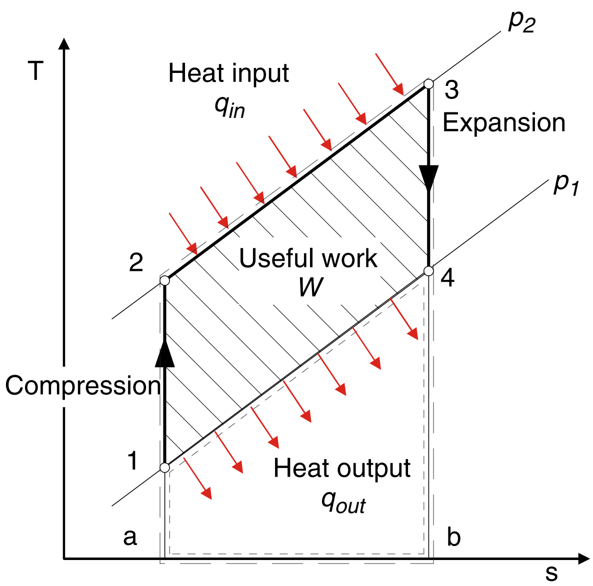


Fig. 4.4 *T-s* diagram of the gas turbine process

The heat quantities can be represented in the *T-s* diagram as areas. The useful work results from the difference of the input quantity of heat area a,2,3,b and output quantity of heat area 4,b,a,1.

Using the *T-s* diagram, it is possible to examine questions about the thermal efficiency and the working capacity of the process. Both temperature conditions and the pressure ratio $\pi = p_2/p_1$ play a role here.

4.1.2 Thermal efficiency (ideal)

The efficiency results from the ratio of the input heat and mechanical work. Assuming a constant heat capacity of the working fluid, for the thermal efficiency we get:

$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\pi^{\frac{\kappa - 1}{\kappa}}} \tag{4.1}$$

With a mean value of $\kappa = 1{,}4$ for air and diatomic gases we get:

$$\eta_{th} = 1 - \frac{1}{\pi^{0{,}285}} \tag{4.2}$$

We can see that the efficiency only depends on the compression ratio π. The highest temperature in the process, the turbine inlet temperature T_3, has no effect on the thermal efficiency.

4.1.3 Specific work capacity

For the specific work capacity the following relationship applies:

$$w_{eff} = c_p \cdot T_3 \cdot \left(1 - \frac{1}{\pi^{0,285}}\right) - c_p \cdot T_1 \cdot (\pi^{0,285} - 1) \quad (4.3)$$

We can see that, besides the compression ratio, the intake and turbine inlet temperature also play a role. The intake temperature is generally determined by the ambient conditions. The turbine inlet temperature T_3 should be chosen as high as possible. In practice it is limited by the temperature resistance of the turbine blades. Consequently the compression ratio is also a decisive factor.

The power output of the system is given by multiplication by the mass flow pushed through.

$$P_{eff} = \dot{m} \cdot w_{eff} \quad (4.4)$$

The relationships depicted here apply for a single-shaft system. They provide guidance for understanding the operating behaviour. For example, the compression ratio is quadratically dependent on the speed. At high speeds this yields a significantly higher system efficiency.

4.1.4 Representation in the *p-v* diagram

The thermodynamic cycle can also be represented in the *p-v* diagram. This makes the compression and expansion process clearly visible.

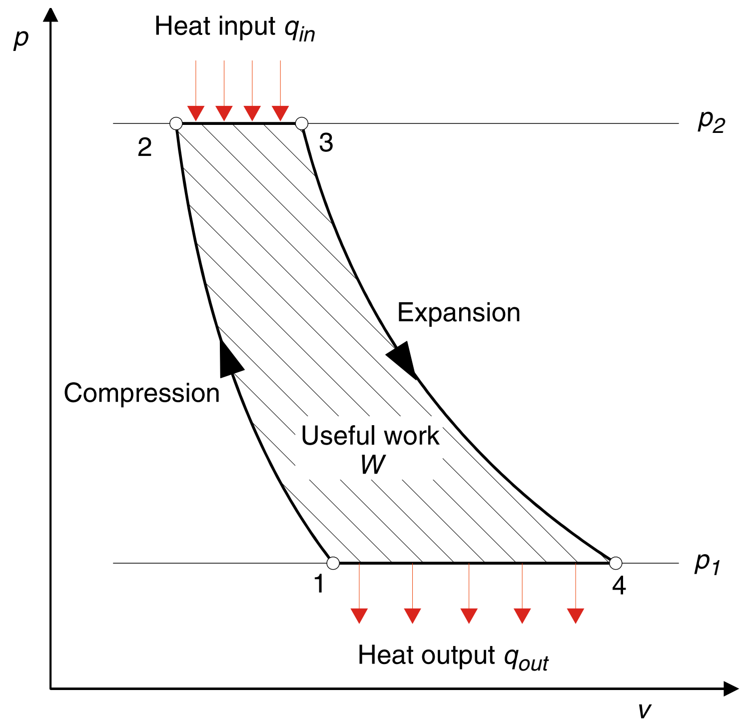


Fig. 4.5 *p-v* diagram of the gas turbine process

The mechanical work can also be represented as an enclosed area. In contrast to the *T-s* diagram, in this case the areas represent mechanical work. We can see that the specific volume of the gas increases between 2 and 3 due to the input of heat, thus decreasing the density. The turbine's surplus useful power results from the fact that it can process a larger volume at the same differential pressure as the compressor.

4.1.5 Gas turbine jet engine

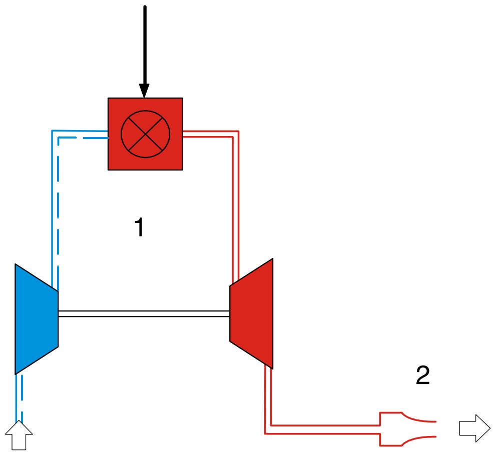


Fig. 4.6 Jet engine

In aircraft engines, above a certain airspeed it is cheaper to use the exhaust jet directly for generating thrust. The simplest jet propulsion consists of a single-shaft gas turbine (1) in an open thermodynamic cycle. The turbine's exhaust gases are only partly used and still contain energy. They are accelerated in a jet nozzle (2) and generate the necessary momentum to propel the aircraft. With an optimum nozzle configuration, the exhaust gases are expanded to ambient pressure.

Using the principle of linear momentum, the thrust can easily be calculated from the pushed through mass flow and the velocities at inlet (c_1) and outlet (c_2):

$$F_t = \dot{m} \cdot (c_2 - c_1) \quad (4.5)$$

In doing so it should be noted that the thrust is a vector quantity and only velocity components in the direction of the thrust make a contribution.

5 Experiments

The selection of experiments makes no claims of completeness but is intended to be used as a stimulus for your own experiments.
The results shown are intended as a guide only. Depending on the construction of the individual components, experimental skills and environmental conditions, deviations may occur in the experiments. Nevertheless, the laws can be clearly demonstrated.

5.1 Recording measurements and their subsequent evaluation

The measurements should only be taken while the gas turbine is in the steady state. The following measured values are examples and are subject to large variations, which are also dependent on the ambient conditions.

The measurement data can be recorded manually or via computer-based measurement data acquisition. Five measurements were taken while idling, at partial load and at full load.

5.1.1 Preparation for the experiment

- Prepare trainer for start-up. (See Chapter 3.5, Chapter 3.6 and Chapter 3.7)

5.1.2 Conducting the experiment

- Run the turbine in the five operating points of idling, 20% partial load, 40% partial load, 60% partial load and full load.
- Record the measured values either with or without a PC

5.1.3 Measured values

Gas turbine experiment	**Date:** Ambient temperature T_{amb} in °C: Air pressure p_{amb} in mbar: Rel. humidity φ in %:		**10/04/2014** 10 1020 65	
Experiment no.:	**1**	**2**	**3**	**4**	**5**
Compressor outlet T_1 in °C	22	40	63	78	101
Combustion chamber T_2 in °C	980	938	931	956	1058
Turbine outlet T_3 in °C	621	582	571	576	598
Combustion chamber pressure p in bar (rel.)	0,08	0,32	0,63	0,90	1,36
Air throughput $dV\ air/dt$ in L/s	11,6	49,0	96,7	150,5	231,7
Air mass flow rate $\dot{m}_a$ in kg/s	0,015	0,061	0,121	0,188	0,290
Fuel consumption $dV\ fuel/dt$ in L/h	6,2	10,9	15,4	19,1	25,1
Fuel mass flow $\dot{m}_f$ in kg/s	$1{,}38 \cdot 10^{-3}$	$2{,}42 \cdot 10^{-3}$	$3{,}42 \cdot 10^{-3}$	$4{,}24 \cdot 10^{-3}$	$5{,}58 \cdot 10^{-3}$
Turbine speed n in min^{-1}	35100	67000	87400	102200	119700
Thrust F_t in N	5,1	20,3	40,4	60,7	97,9
Notes	Idle	20% partial load	40% partial load	60% partial load	Full load

Tab. 5.1

5.1.4 Analysis of the experiment

5.1.4.1 Air mass flow and fuel mass flow

The air mass flow $\dot{m}_a$ in kg/s is calculated as follows:

$$\dot{m}_a = \frac{\rho_0}{1000} \cdot \frac{T_0 \cdot p_{amb}}{p_0 \cdot T_{amb}} \cdot \text{Anzeige} \qquad (5.1)$$

with the reference values under standard conditions:

Density at 20°C $\rho_0 = 1{,}199 \ \text{kg/m}^3$

Temperature at 20°C in K $T_0 = 293 \ \text{K}$

Pressure at $p_0 = 1{,}013 \ \text{bar}$

under the experimental conditions:

Temperature at 10°C in K $T_{amb} = 283 \ \text{K}$

Pressure at $p_{amb} = 1{,}020$ bar

Summary of above formula

$$\dot{m}_a = 0{,}347 \cdot \frac{p_{amb}}{T_{amb}} \cdot \text{Anzeige} \qquad (5.2)$$

Here
T_{amb} is the ambient temperature in K,
p_{amb} the ambient pressure in bar and
"Anzeige" (display) is the measured air volume flow in L/s.

Based on the full load case we get:

$$\dot{m}_a = 0{,}347 \cdot \frac{1{,}020}{283} \cdot 231{,}7 = 0{,}290 \ \text{kg/s}$$

The fuel mass flow $\dot{m}_f$ is calculated at a display of fuel consumption *dV fuel/dt* in L/h and a desired fuel mass flow $\dot{m}_f$ in kg/s as follows:

$$\dot{m}_f = \frac{\rho_f}{3600} \cdot \text{Anzeige} \tag{5.3}$$

where ρ_f in kg/dm³ is the density of the fuel at 15°C

Based on the full load case we get:

with a density of, for example, $\rho_f = 0{,}8\ \text{kg/dm}^3$

$$\dot{m}_f = \frac{0{,}8}{3600}\frac{\text{kg}}{\text{dm}^3} \cdot 25{,}1\frac{\text{L}}{\text{h}} = 5{,}58 \cdot 10^{-3}\text{kg/s}$$

5.1.4.2 Other characteristics of the gas turbine

Calculation based on full load operation.

Specific thrust:

$$f_t = \frac{F_t}{\dot{m}_a} \quad \text{where } \dot{m} = \dot{m}_a + \dot{m}_f \approx \dot{m}_a \tag{5.4}$$

$$f_t = \frac{97{,}9\ \mathrm{N}}{0{,}290\frac{\mathrm{kg}}{\mathrm{s}}} = 338\frac{\mathrm{N \cdot s}}{\mathrm{kg}}$$

Specific fuel consumption:

$$b_s = \frac{\dot{m}_f}{F_t} \tag{5.5}$$

$$b_s = \frac{5{,}58 \cdot 10^{-3}\frac{\mathrm{kg}}{\mathrm{s}}}{97{,}9\ \mathrm{N}} = 5{,}70 \cdot 10^{-5}\frac{\mathrm{kg}}{\mathrm{N \cdot s}}$$

$$b_s = 0{,}205\frac{\mathrm{kg}}{\mathrm{N \cdot h}}$$

Thrust/weight ratio:

$$f_G = \frac{F_t}{G} \tag{5.6}$$

G : Weight in kg

$$f_G = \frac{97{,}9\mathrm{N}}{13{,}6\mathrm{kg}} = 7{,}20\frac{\mathrm{N}}{\mathrm{kg}}$$

Output thermal power:

$$\dot{Q}_f = \dot{m}_f \cdot H_i \tag{5.7}$$

$$\dot{Q}_f = 5{,}58 \cdot 10^{-3}\frac{\mathrm{kg}}{\mathrm{s}} \cdot 42580\frac{\mathrm{kJ}}{\mathrm{kg}} = 237{,}6\mathrm{kW}$$

H_i : Calorific value 42580 kJ/kg (formerly H_u)

Thermal efficiency (ideal):

$$\eta_{th} = 1 - \frac{1}{\pi^{\frac{\kappa - 1}{\kappa}}} = 1 - \frac{1}{\pi^{0,285}} \tag{5.8}$$

where $\kappa = 1{,}4$

where π compression ratio $\pi = \frac{p\text{ (abs.)}}{p_{amb}\text{ (abs.)}}$

where p_{amb}: Pressure before compression

p : Pressure after compression

$$\eta_{th} = 1 - \frac{1}{2{,}33^{0{,}285}} = 0{,}214$$

5.1.4.3 Representation of the measured data in diagrams

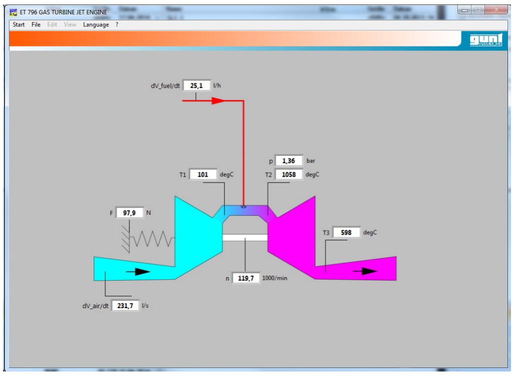


Fig. 5.1 Gas turbine system diagram

The measured data can be displayed online and saved with the PC-based measurement data acquisition. Then the recorded measured values can be processed with the Measurements Graph part of the program. The *.dat files with the stored measurement data are used as the basis of the data.

The following measured values are contained in the *.dat file: It is possible to process the data using a text editor. The data can also be imported and processed using a spreadsheet program such as Excel.

1	Time	*t* in h:min:sec
2	Compressor outlet temp.	T_1 in °C
3	Combustion chamber temp.	T_2 in °C
4	Turbine outlet temp.	T_3 in °C
5	Turbine speed	n in min^{-1}
4	Fuel consumption	*dV_fuel/dt* in L/h
5	Combustion chamber pressure	p in bar (rel.)
6	Thrust	F_t in N
7	Air consumption	*dV air/dt* in L/s

The following figures show some measurement results that have been recorded with the PC-based measurement data acquisition.

The following figure shows recorded measurement data in the "Measurements Graph" window. The thrust of the gas turbine is shown as a function of the speed. The thrust increases disproportionately with the speed. There is almost no thrust at idle speed. The measurements shown were taken at intervals of 2s. The plotted charts were measured at a P80 gas turbine with less thrust and do not match the currently recorded measured values of Chapter 5.1.3. Nevertheless, the laws can clearly be seen.

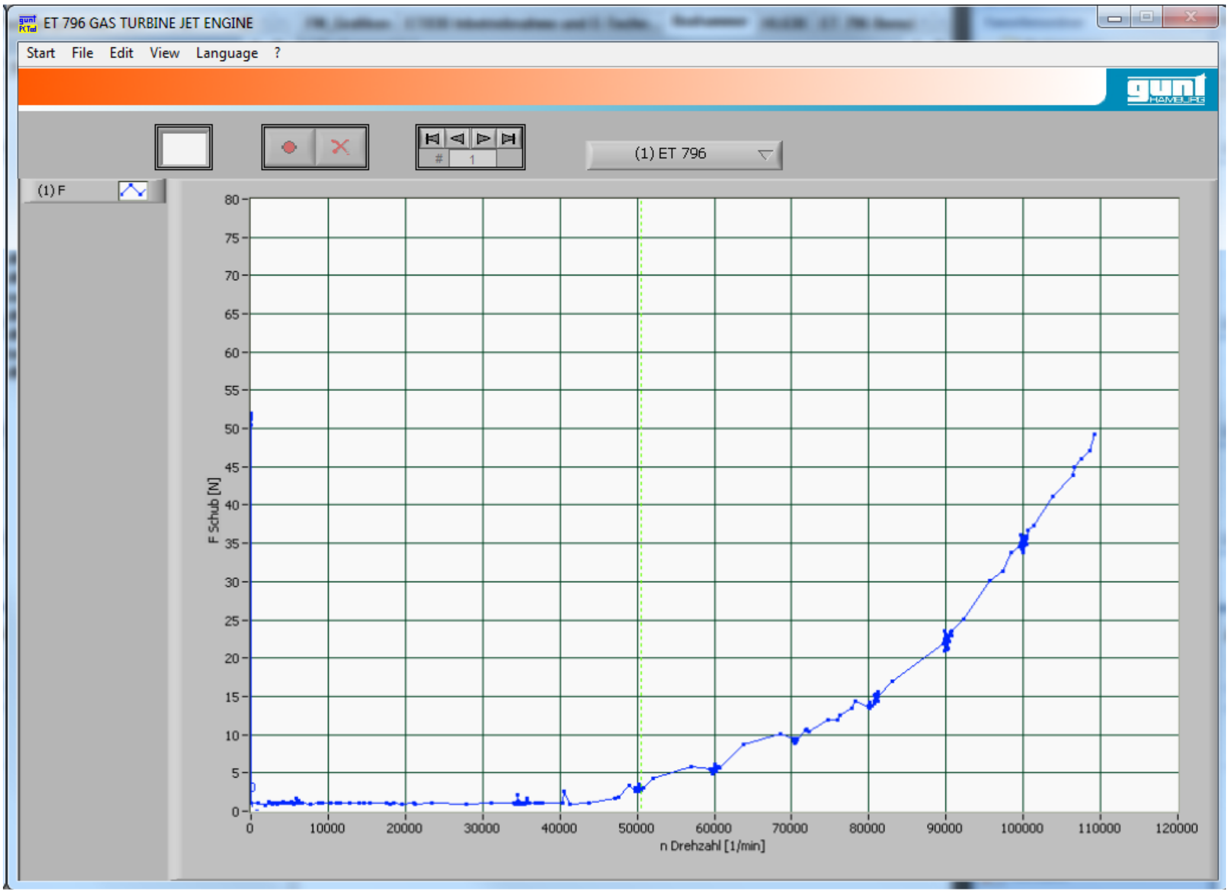


Fig. 5.2 Thrust of the gas turbine from start-up to 120 000 revolutions

The following figure shows the relationship between fuel consumption and thrust.

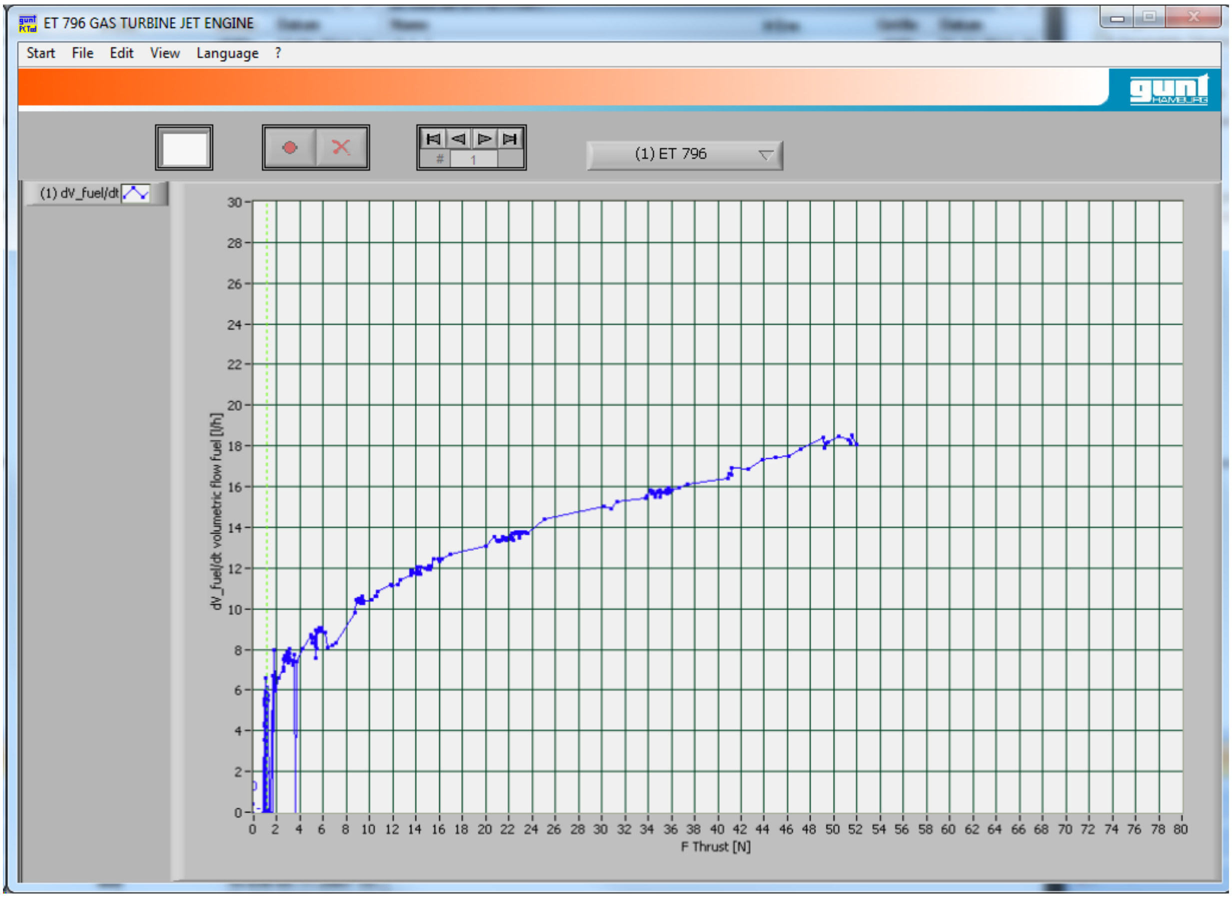


Fig. 5.3 Fuel consumption as a function of thrust

The following figure illustrates the relationship between air demand and thrust. The temperatures are also shown.

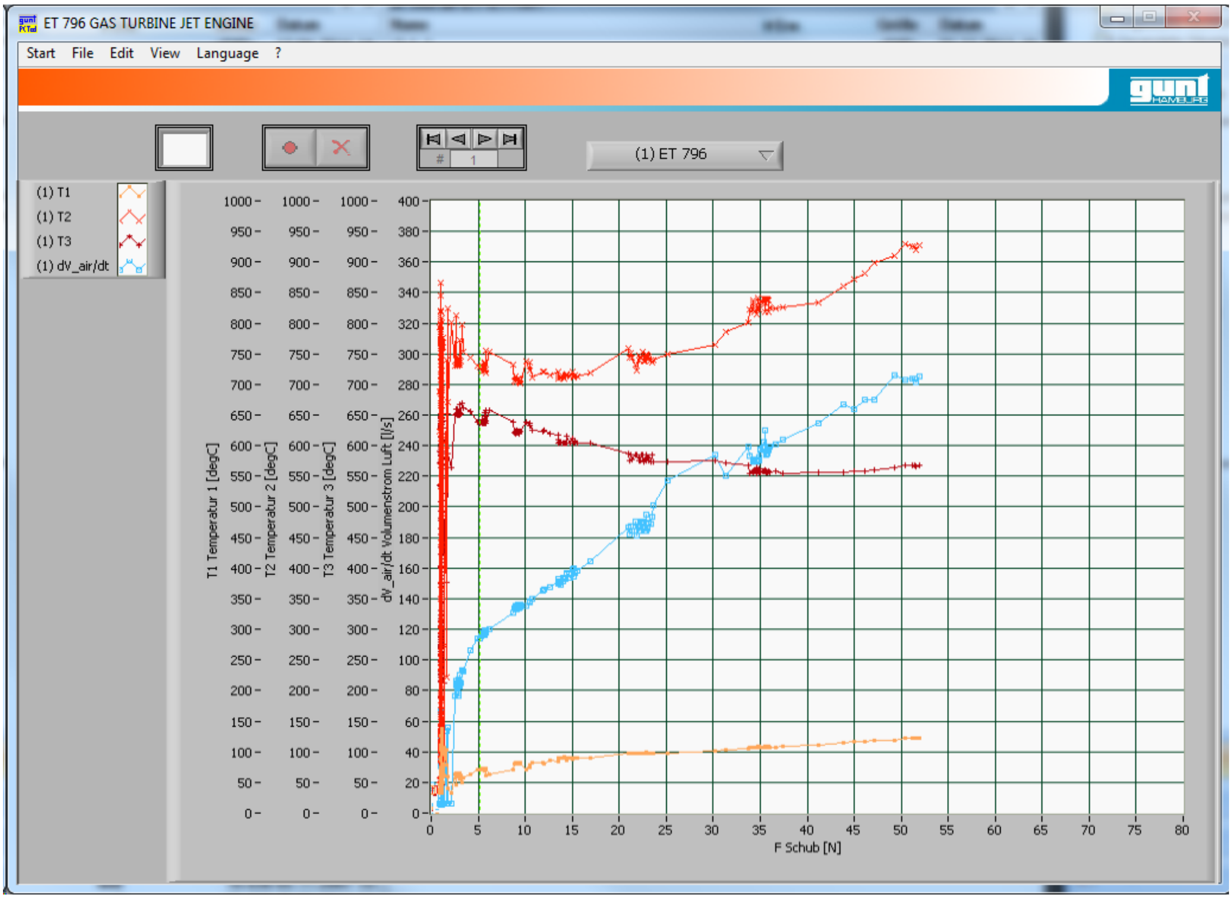


Fig. 5.4 Temperatures and the gas turbine's air demand as a function of thrust
T_1 Compressor temp. in °C
T_2 Combustion chamber temp. in °C
T_3 Turbine outlet temp. in °C
dV_air/dt Air volumetric flow rate in L/s

The last diagram shows the combustion chamber pressure over the speed. This results in a quadratic dependency.

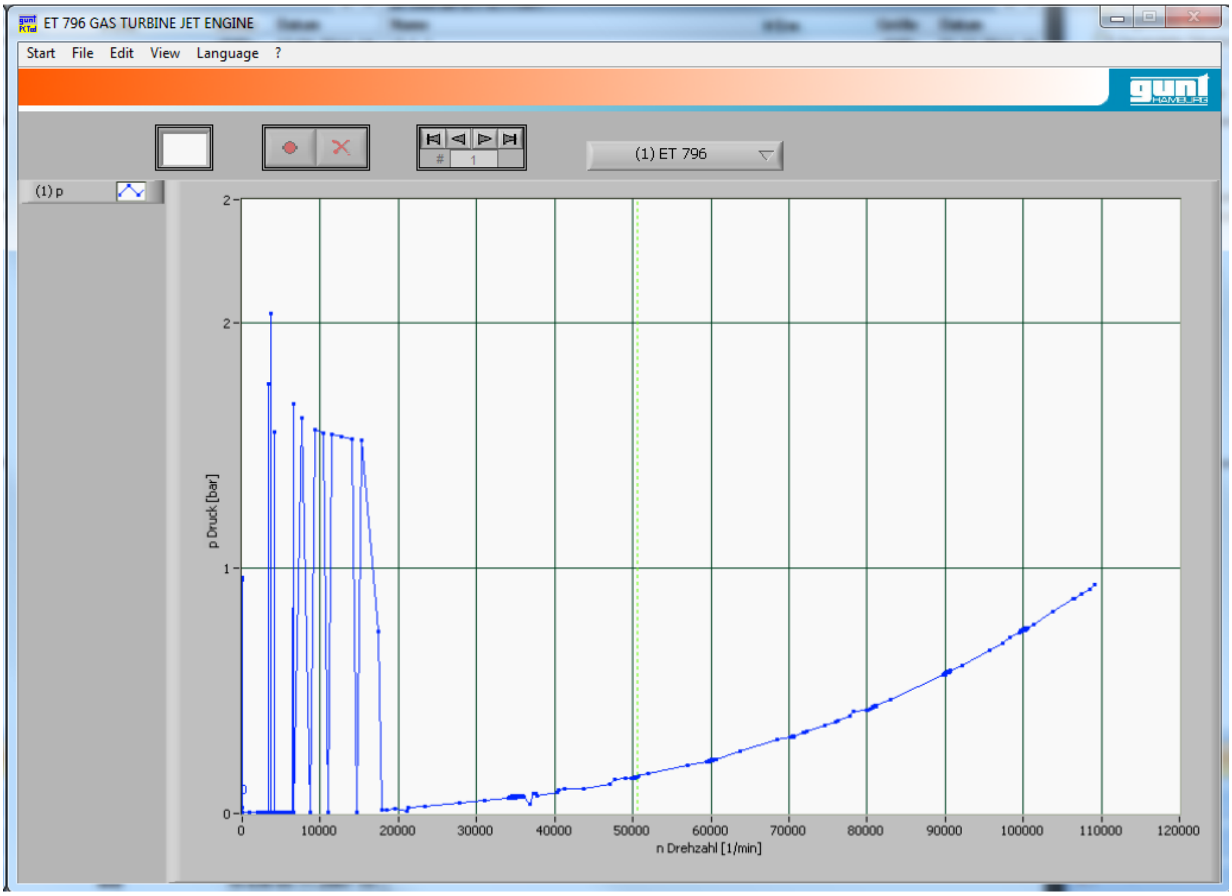


Fig. 5.5 Combustion chamber pressure of the gas turbine from start-up to 120,000 revolutions

5.1.4.4 Determining the fuel-air ratio

The fuel-air ratio is determined from the quotients of the actual amount of air taken in to the amount of air required for stoichiometric combustion of the fuel. The amount of air required for combustion of kerosene is:

$$L_{min} = 14{,}2\frac{kg_{air}}{kg_{fuel}}$$

It follows for the fuel-air ratio at full load:

$$\lambda = \frac{1}{L_{min}} \cdot \frac{\dot{m}_a}{\dot{m}_f} = \frac{0{,}290\frac{kg}{s}}{14{,}2 \cdot 5{,}58 \cdot 10^{-3}\frac{kg}{s}} = 3{,}66 \qquad (5.9)$$

The fuel-air ratio λ of the combustion chamber is nearer to the stabilised flame in gas turbines λ = 1. The secondary air increases the values up to about 5, so that the temperature in the combustion chamber remains below 1600°C and below 1400°C when entering the turbine.

6 Appendix

6.1 Technical data

Dimensions

Length x Width x Height	1230 x 800 x 1330 mm
Weight	112 kg

Power supply

Voltage	230 V
Frequency	50 Hz
Phases	1
Rated input (power)	400 W
Alternatives optional, see rating plate	

Fuel Mixture of kerosene (Jet-A, Jet A-1) or petroleum with turbine oil
Density at 15°C 0,775...0,84 kg/m^3

Exhaust stack Pipe Ø 300 mm
Volume at 1m distance (full load): approx. 130 dB(A)

Type

Gas turbine, open cycle

Gas turbine P80-SE

Design: Radial compressor and axial turbine

Annular combustion chamber

Speed range:	35 000...120 000 (max.) min^{-1}
Max. pressure ratio:	approx. 2,2
Max. fuel consumption:	approx. 0,4 L/min

Ignition and starting system

Special glow plug with starting fuel 1,2 V

Electric starter

⚠ WARNING

Smoking or open flames when handling combustible fuels can lead to explosion or deflagration.

Possibility of severe injuries.

- No open flame
- No smoking
- Erect warning sign
- Comply with relevant statutory provisions when transporting and storing fuels (kerosene, petroleum, etc.).

Either kerosene (Jet-A1) or petroleum can be used as fuel, to which is added approx. 5% oil, special turbine oil (e.g. AeroShell 500 or Exxon Turbine Oil).

Rule of thumb: 1 litre of oil to 20 litres of fuel

NOTICE

To prevent static charging of the fuel system during operation, an antistatic additive (from Jetcat, product no. 61198- 00) can be added to the fuel.

NOTICE

Fully-synthetic two-stroke oils are not suitable and should not be used.

Lubrication system

Oil-mist lubrication with oil-fuel mixture **mixing ratio 1:20**.

Example for filling the fuel tank: 4,75L petroleum and 0,25L turbine oil.

Recommended oil types:

AeroShell Turbine Oil 500/560 with the specification MIL-PRF 23699 Grade HTS or Mobil Jet 1.

Conditionally suitable:

Exxon Turbine Oil is suitable only for kerosene.

Not recommended:

Castrol TTS is not suitable, since it is not miscible with the fuels.

Safety devices

Shutdown at

- Overtemperature at the turbine inlet
- Overspeed in the turbine

Instrumentation

Thermocouples and digital displays for measuring the following temperatures:

– Compressor outlet	0...1200°C
– Combustion chamber	0...1200°C
– Turbine outlet	0...1200°C

Pressure sensors and digital display

– Combustion chamber pressure: 0... 2 bar

Mass flows

– Air inlet measuring nozzle with square root extracting
pressure sensor and digital display:
0...500 L/s

– Fuel from the fuel pump
Control: 0...25 L/h

– Turbine digital revolution counter:
0...199999 min^{-1}

Measurement data acquisition

Programme environment:

LabVIEW Runtime

System requirements:

PC with Pentium IV, 1 GHz processor

Minimum 1024 MB RAM

Minimum 1 GB free
hard disk space

1 CD-ROM drive

1 USB port

Graphic card resolution
min. 1024 x 768 pixels, True Color

Windows Vista / Windows 7 / Windows 8

6.2 List of abbreviations

Abbreviation	Meaning
ECU	Electronic Control Unit
GSU	Ground Support Unit
dV_fuel/dt	Fuel consumption $\dot{V}_F$
dV_air/dt	Air flow $\dot{V}_a$

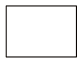
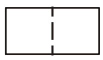
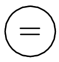
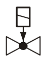
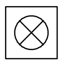
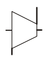
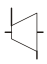
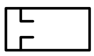
6.3 List of formula symbols and units

Formula symbol	Mathematical/physical value	Unit
b_s	Specific fuel consumption	$kg/(N \cdot s)$
c_p	Specific thermal capacity	$kg/(kg \cdot K)$
dV_fuel/dt	Fuel consumption	L/h
dV_air/dt	Air flow	L/s
f_t	Specific thrust	$N \cdot s/kg$
f_G	Thrust/weight ratio	N/kg
F	Force	N
G	Weight	kg
H_i	Calorific value (i: inferior)	kJ/kg
L_{min}	Stoichiometrically required amount of air	kg_a/kg_f
$\dot{m}$	Mass flow	kg/s
$\dot{m}_a$	Air mass flow	kg/s
$\dot{m}_f$	Fuel mass flow	kg/s, g/s
n	Speed	min^{-1}
p	Pressure	bar
p_0	Pressure at standard conditions	mbar, bar, Pa
p_{amb}	Ambient pressure (atmospheric pressure)	mbar, bar, Pa
p	Pressure after compression	mbar, bar, Pa
q_{in}	Specific heat input	J/kg

Formula symbol	Mathematical/physical value	Unit
q_{out}	Specific heat output	J/kg
$\dot{Q}_f$	Output thermal power	W, kW
s	Specific entropy	$J/(kg \cdot K)$
F_t	Thrust	N
t	Time	h:m:s
T_0	Temperature under standard conditions	°C, K
T_{amb}	Ambient temperature	°C, K
T_1	Compressor temperature	°C, K
T_2	Combustion chamber temperature	°C, K
T_3	Turbine outlet temperature	°C, K
v	Specific volume	m^3/kg
w	Specific useful work	J/kg
w_{eff}	Specific work capacity	J/kg
η_{th}	Thermal efficiency	%
κ	Isentropic exponent	-
λ	Fuel-air ratio	-
π	Pressure ratio	-
ρ_0	Density under standard conditions	kg/dm^3
φ	Relative humidity	% RH

Index	Explanation
a	Air
amb	Ambient
eff	Effective
in	fed in
out	emitted
t	Thrust
theo	theoretical

6.4 List of symbols in the process schematic

Symbol	Description
	Fuel pump
	Fuel tank
	Filter
	Motor
	Fuel valve
	Combustion chamber
	Compressor
	Turbine
	Measuring nozzle

6.5 List of identification letters used in the process schematic

Identification letter	Description
Equipment and machinery	
B	Container, tank, hopper, silo
M	Electric motor
P	Pump
V	Compressor, vacuum pump, fan
Fittings	
V	Valve, general

Tab. 6.1 Identification letters for equipment, machinery, fittings and pipes

Identification letter	Measurand or other input variable, actuator		Processing
	as first letter	as supplementary letter	as subsequent letter (sequence I, R, C)
X	Force		
P	Pressure		
F	Flow rate, flow capacity	Ratio	
S	Velocity, speed, frequency		Circuit, flow control, logic control
T	Temperature		Measuring transducer function

Tab. 6.2 Identification letter for measurement points

6.6 Tables and graphs

Unit	mm^3	cm^3	L	m^3
1 mm^3	1	0,001	0,000001	0,000000001
1 cm^3	1.000	1	0,001	0,000001
1 L	1.000.000	1.000	1	0,001
1 m^3	1.000.000.000	1.000.000	1.000	1

Tab. 6.3 Conversion table for units of volume

Unit	L/s	L/min	L/h	m^3/min	m^3/h
1 L/s	1	60	3600	0,06	3,6
1 L/min	0,01667	1	60	0,001	0,06
1 L/h	0,000278	0,01667	1	0,00001667	0,001
1 m^3/min	16,667	1000	0,0006	1	60
1 m^3/h	0,278	16,667	1000	0,01667	1

Tab. 6.4 Conversion table for units of volume flow

Unit	bar	mbar	Pa	hPa	kPa	mm WC *
1 bar	1	1.000	100.000	1.000	100	10.000
1 mbar	0,001	1	100	1	0,1	10
1 Pa	0,00001	0,01	1	0,01	0,001	0,1
1 hPa	0,001	1	100	1	0,1	10
1 kPa	0,01	10	1.000	10	1	100
1 mm WC *	0,0001	0,1	10	0,1	0,01	1

Tab. 6.5 Conversion table for units of pressure
* rounded figures

6.7 Worksheets

Gas turbine experiment	Date: Ambient temperature T_{amb} °C: Air pressure p_{amb} in mbar: Rel. humidity φ in %:				
Experiment no.:	**1**	**2**	**3**	**4**	**5**
Compressor outlet T_1 in °C					
Combustion chamber T_2 in °C					
Turbine outlet T_3 in °C					
Combustion chamber pressure p in bar					
Air throughput *dV_air/dt* in L/s					
Air mass flow $\dot{m}_a$ in kg/s					
Fuel consumption *dV_fuel/dt* in L/h					
Fuel mass flow $\dot{m}_f$ in g/s					
Turbine speed n in min^{-1}					
Thrust F_t in N					
Notes					

Tab. 6.6