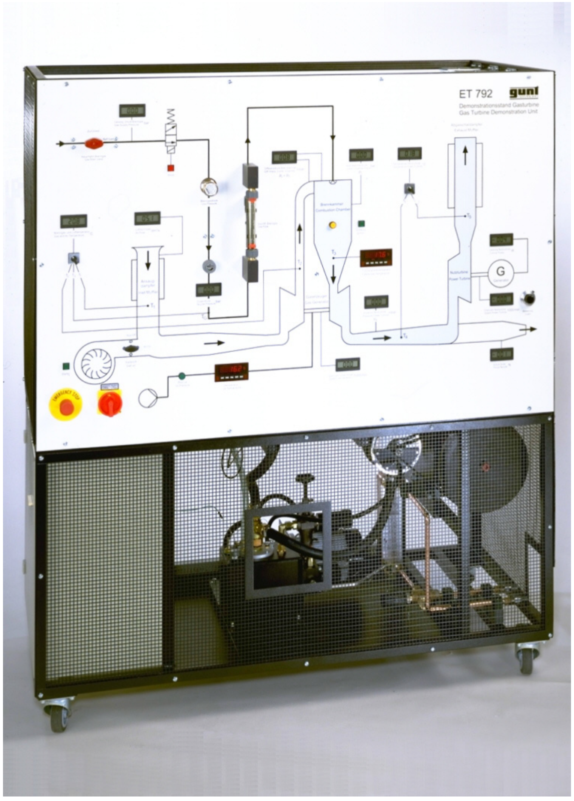
Experiment Instructions

ET 792 Gas Turbine



Experiment Instructions

Last modification by: Dipl.-Ing. Peter Mittasch

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

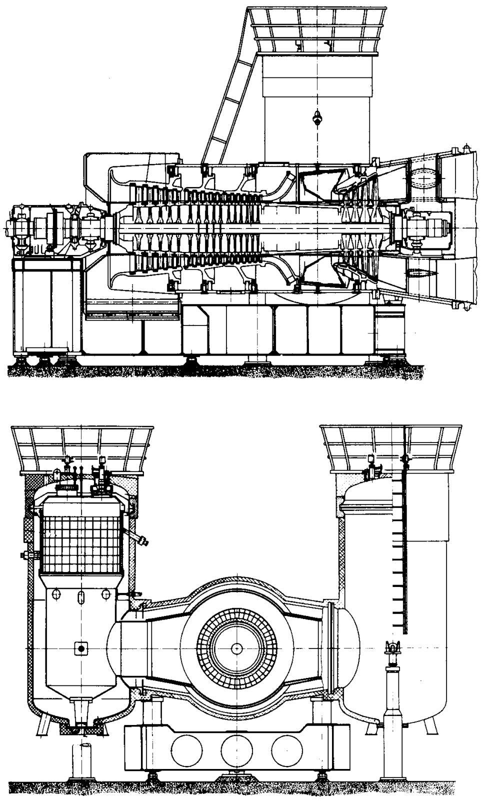


Fig. 1.1 Large industrial gas turbine plant with 56MW power rating

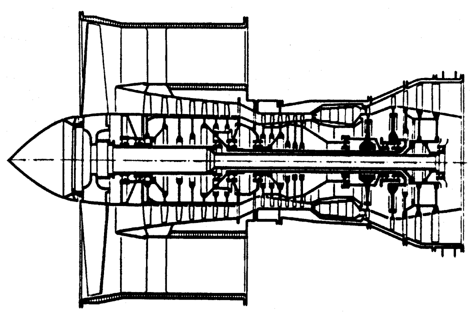


Fig. 1.2 Jet engine for the propulsion of an aircraft

Using the **ET 792 Gas Turbine** demonstration unit, the function and behaviour of a scale model gas turbine can be demonstrated and studied. Gas turbine plant are used to generate mechanical and electrical energy:

- Driving electricity generators in power stations
- Driving compressors and pumps in oil and gas production
- Driving ships, locomotives and heavy vehicles
- For the propulsion of aircraft with propeller and jet engines

Gas turbines are always used if high power density, low weight and quick starting are required. Contrary to piston engines, as fluid flow machines they permit high material flow rates in small dimensions. In this way light and, at the same time, powerful drives can be realised.

As the moving parts of a gas turbine only perform rotary motion, almost vibration free running can be achieved if the turbine is well balanced. Disadvantages are the high noise emissions due to the high gas speeds and the simultaneous connection to the atmosphere.

In comparison to steam turbines, gas turbines work at higher temperatures but with lower pressures. The high temperatures especially in the area of the turbine require particularly heat resistant materials.

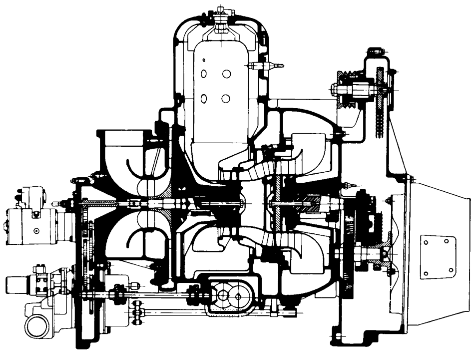


Fig. 1.3 2-shaft vehicle turbine with 200 kW power rating

The demonstration unit is a two shaft system with radial compressors and turbines. The power turbine drives a generator for generating electrical power. In addition, the system can be used to demonstrate a single shaft jet engine. All components necessary for the operation of the system are combined in a compact arrangement on a trolley on castors. Operation with propane gas ensures clean, odour-less operation and good exhaust gas quality.

The system is of straightforward construction and is specially designed for training purposes. The control and display of all important process parameters is combined on a control panel. A clearly laid out process schema on the control panel eases the allocation of the measured values and assists in the performance of the experiment.

An optionally available PC data acquisition card with analysis software facilitates the on-line logging of all relevant process parameters and their graphic display.

Apart from the pure demonstration of the operating behaviour, it is also possible to perform qualitative investigations, such as the determination of the electrical power output, the specific gas consumption or the system efficiency.

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
	Explosive materials
	Hazard (general)
	Toxic materials
	Hand injuries
	Hot surfaces
	Notice
	Wear ear protection

2.3 Safety Instructions

⚠ WARNING

Reaching into the open switch box can result in electric shocks.

- Disconnect from the mains supply before opening.
- Work should only be performed by qualified electricians.
- Protect the switch box against moisture.

⚠ WARNING

Gas escape due to defects.

Risk of explosion due to sparking and naked flame.

- Do not press any electrical switches.
- Close the gas valve on the gas bottle and shut down the system.
- Replace worn or brittle gas hoses and fittings.
- Only store gas bottles in well ventilated rooms or outdoors.
- Before operating again, have the system checked for leaks by a qualified gas fitter.

⚠ WARNING

Risk of poisoning by CO or CO_2 during gas turbine operation.

- Only operate the system with the exhaust pipe running into the open air.
- Ensure adequate ventilation.

⚠ WARNING

Risk of burns from exhaust jet up to 700 °C.

- Allow the exhaust gas connection and any exhaust pipe fitted on the gas turbine to cool down before touching.
- When operated without exhaust pipe, do not enter the safety zone around the exhaust jet.

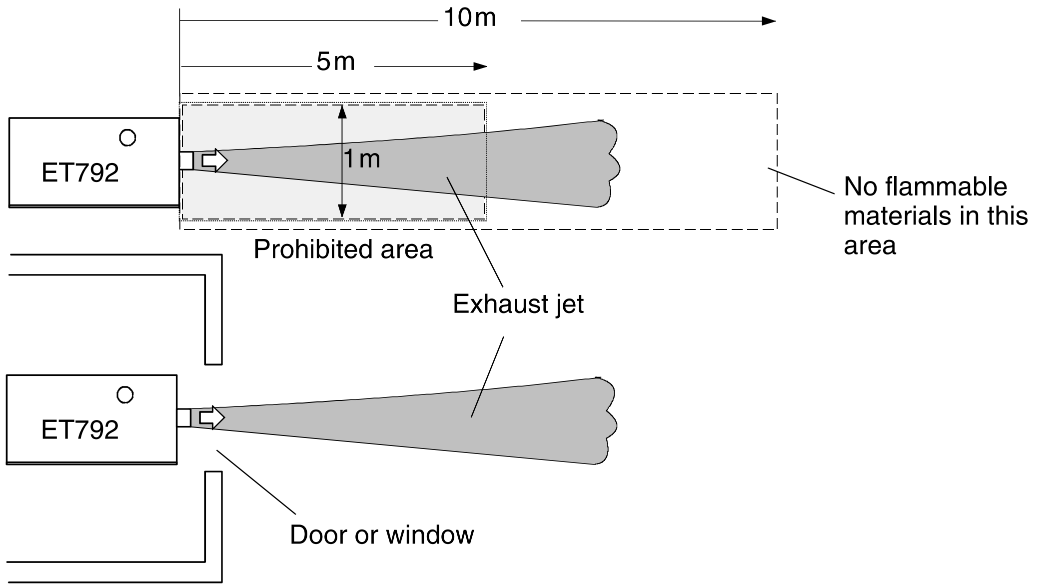


Fig. 2.1 Safety zones at the jet outlet

⚠ WARNING

Testing and adjusting the belt during operation causes severe hand injuries.

- To test and adjust the slackness of the belt, first shut down the gas turbine and then shut down the entire unit using the main switch and the emergency stop mechanism.

⚠ WARNING

During operation as jet engine a very high noise level is generated (< 110dB(A)).

Risk of hearing damage.

- Wear suitable ear protection during operation.

NOTICE

Risk of fire.

- Do not bring flammable materials into contact with the hot exhaust pipe or place them in the exhaust jet.
- Especially when **operated as a jet engine**, the outlet area must be kept clear of flammable or heat-sensitive materials.
- Minimum distance between flammable materials and exhaust jet: 10m.
- In the case of oil leakage at the turbine, oil can catch fire on the hot turbine housing.

NOTICE

The gas connection must be made and checked by a qualified gas fitter.

NOTICE

Oil vapour discharge from oil tank

Due to the nature of the system, whitish oil vapour escapes from the oil tank during starting fan operation when the oil is warm.

NOTICE

Before switching on the unit the following points are to be followed:

- A qualified gas fitter must check the unit for leaks.
- Do not operate the gas turbine unsupervised.
- An approved and tested fire extinguisher with a min. capacity of 6kg is to be placed in the immediate vicinity of the gas turbine.
- The power turbine needs a minimum speed to build up a sustainable film of lubrication.
  Minimum continuous speed without load:
  10.000 min^{-1}
  Minimum continuous speed under load:
  15.000 min^{-1}
- Ensure the power turbine is correctly tensioned.
  The power turbine belt tension is a compromise between maximum torque transfer and minimum turbine bearing load. Since the power turbine bearings are not designed for high radial loads, the belt tension should be selected only high enough to transfer the rated power output (1,5kW at 30.000rpm) with no significant slip. As the torque increases at low speeds, the power output should be reduced by throttling the gas generator speed in order to avoid slip.

NOTICE

On the jet turbine the exhaust jet leaves the turbine horizontally at very high speed and temperature.

- An area of 5m in the direction of the jet and 1...1,5m to the sides is to be fenced off.
- Within a distance of 10m in the direction of the jet, there must be no objects sensitive to heat or flammable materials.
- The exhaust jet should be directed to the outside through a window or doorway. An exhaust pipe can be connected to the existing guide fitting. In certain circumstances a loss in power output must be expected.

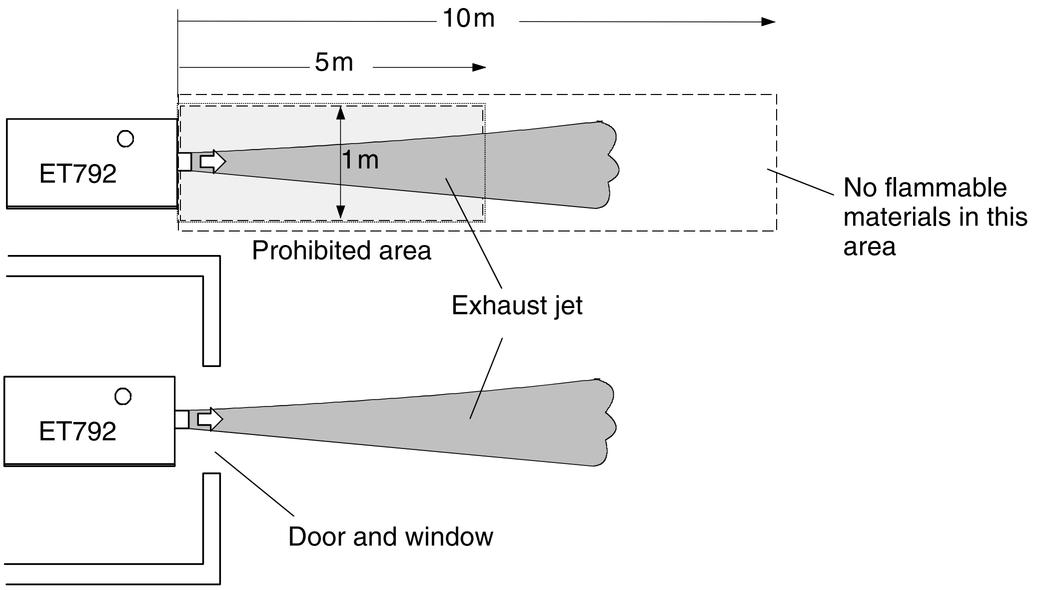


Fig. 2.2 Safety zones at the jet outlet

NOTICE

If the turbine is in jet mode, the power turbine must be turned off. The potentiometer for generator load must be set to zero.

NOTICE

- On the occurrence of critical operating states (over speed, over temperature, leaks, etc.), always operate the rapid action stop valve first.
- To avoid interrupting the lubrication of the turbines on run down, only switch off the electrical system once the turbines are at standstill.

NOTICE

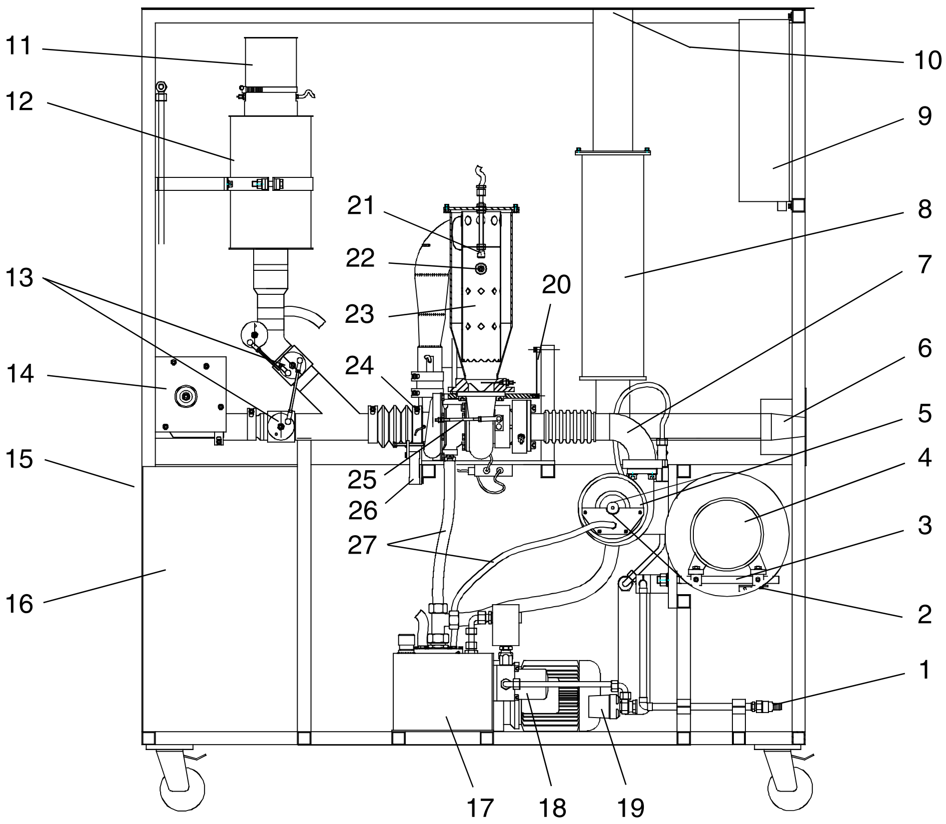
- The system is not suitable for operation outdoors.
- The system is to be operated in dry, dust-free and well ventilated rooms.
- In particular, attention is to be paid to good ventilation as the system has an air consumption of 300 m^3/h.

NOTICE

As gas is heavier than air and collects on the floor, it is not permitted to store gas bottles in trays or recesses in the floor. Closed rooms must have ventilation openings at floor level.

3 Description of the Unit

3.1 Structure of the Unit



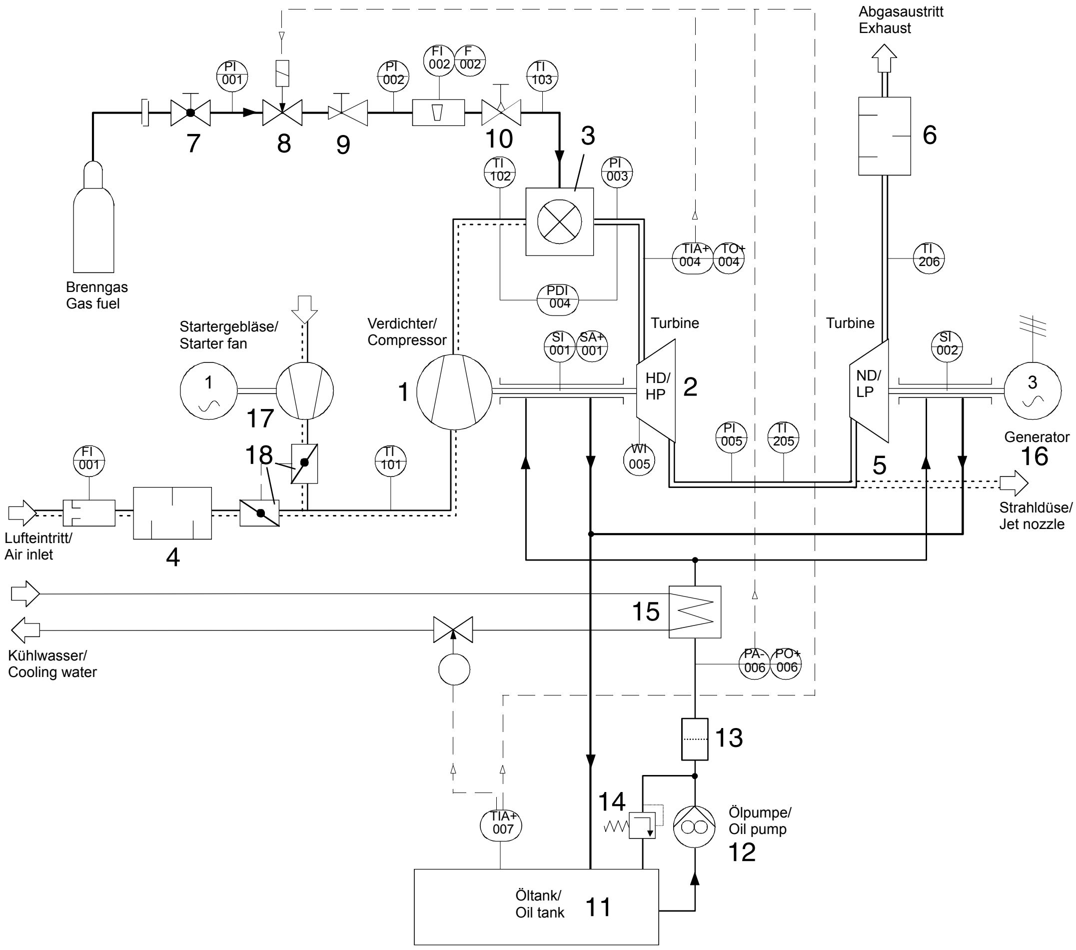
1	Cooling water inlet and outlet	15	USB port
2	Speed sensor power turbine	16	Switch box
3	Belt tensioner	17	Oil tank
4	Generator	18	Oil filter
5	Power turbine	19	Oil cooler thermostat
6	Jet pipe and nozzle	20	Leaf spring mounting
7	Connecting pipe to power turbine	21	Gas nozzle
8	Exhaust muffler	22	Ignition plug
9	Braking resistors	23	Combustion chamber
10	Exhaust outlet	24	Speed sensor gas generator
11	Intake funnel with measuring orifice	25	Gas generator
12	Intake muffler	26	Force transducer
13	Change-over damper	27	Oil return pipes
14	Starting fan		

Fig. 3.1 Structure of the gas turbine system

All system components are arranged in a steel frame. The frame is closed towards the front by the front panel. The other sides are closed by removable perforated sheets. These ensure good cooling and ventilation together with protection against contact with hot or rotating parts.

Fig. 3.1 shows the layout of the components with the front panel removed.

3.2 Process Schematic



1	Compressor	10	Control valve
2	Turbine	11	Tank
3	Combustion chamber	12	Oil pump
4	Muffler	13	Oil filter
5	Power turbine	14	Pressure regulator
6	Exhaust muffler	15	Oil cooler
7	Main valve	16	Generator
8	Rapid action stop valve	17	Starting fan
9	Pressure regulator	18	Change-over damper

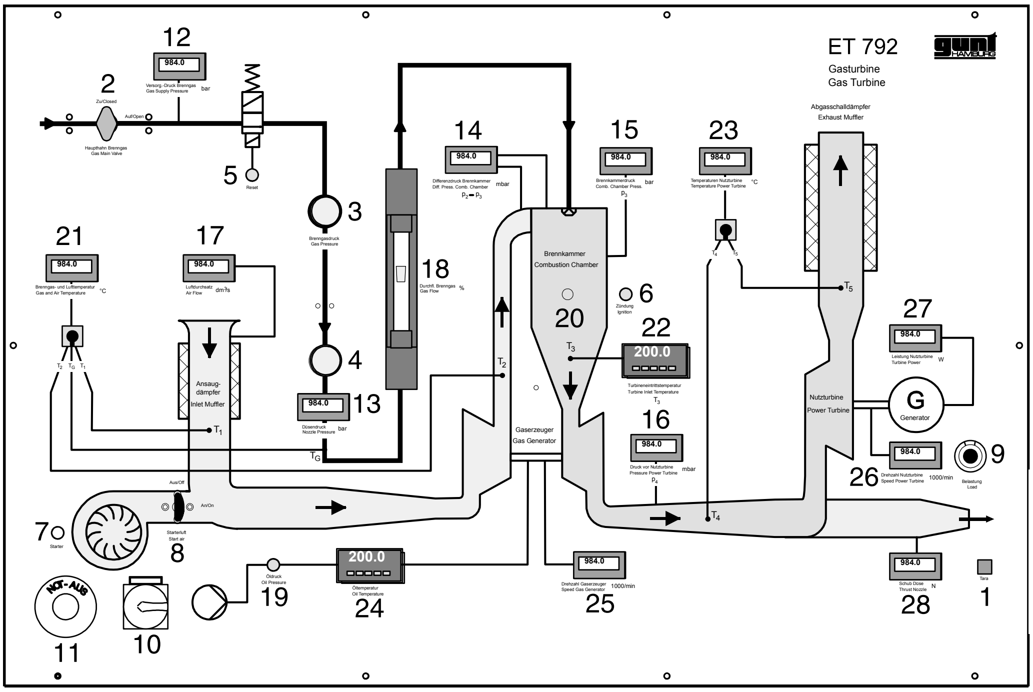
Fig. 3.2 Process schematic of the gas turbine demonstration unit

The demonstration unit contains a complete gas turbine system with the following subsystems:

- **Gas generator** consisting of compressor (1), turbine (2), combustion chamber (3) and intake system with muffler (4).
- **Power turbine** (5) with exhaust muffler (6) and belt drive to the generator (it is also possible to fit a jet pipe with thrust nozzle instead of the power turbine).
- **Fuel system** consisting of a main valve (7), rapid action stop valve (8), pressure regulator (9), control valve (10) and burner nozzle.
- **Ignition system** with ignition plug and ignition transformer.
- **Lubricating system** consisting of tank (11), oil pump (12), oil filter (13), pressure regulator (14) and thermostatically regulated oil cooler (15).
- **Generator** (16) with converter, ballast resistors and power indicator.
- **Starter system** with starting fan (17) and change-over damper (18).
- **Measuring instruments and controls** with temperature, flow rate, speed and pressure measuring points and associated displays. These also include the safety components such as temperature and pressure limiters, oil pressure and oil temperature monitoring.

3.3 Components of the Unit

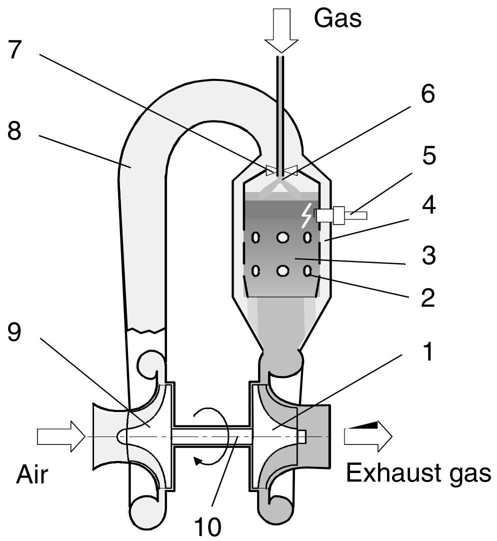
3.3.1 Controls



1	Tara thrust display	15	Pressure before the turbine
2	Main gas valve	16	Pressure before the power turbine
3	Gas pressure regulator	17	Air flow rate, speed at the inlet
4	Gas control valve	18	Gas flow rate
5	Rapid shut down button	19	Oil pressure indicator lamp
6	Ignition button	20	Ignition indicator lamp
7	Starting fan switch	21	Temperatures at air inlet, gas inlet and compressor
8	Change-over damper rotary knob for starting air	22	Temperature at turbine inlet
9	Potentiometer for generator load	23	Temperatures at power turbine inlet and power turbine outlet
10	Master switch	24	Oil temperature
11	Emergency stop switch	25	Speed at gas generator
12	Gas supply pressure (bottle pressure)	26	Speed at power turbine
13	Gas nozzle pressure	27	Power at generator
14	Differential pressure, combustion chamber	28	Thrust

Fig. 3.3 Controls and displays on the front panel

3.3.2 Gas Generator



1	Radial wheel
2	Holes
3	Combustion chamber
4	Combustion chamber pipe
5	Ignition plug
6	Combustion nozzle
7	Turbulence generator
8	Diffuser
9	Compressor wheel
10	Shaft

Fig. 3.4 Function schema of a gas generator

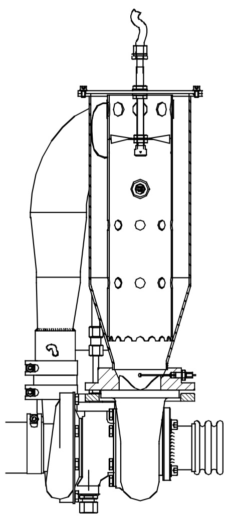


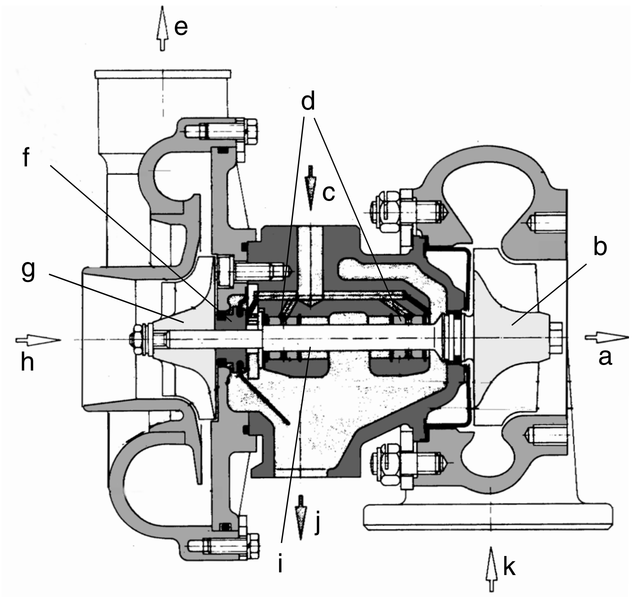
Fig. 3.5 Gas generator

The core of the system is formed by the gas generator. This consists of a radial turbine with directly coupled radial compressor and a combustion chamber. The turbine and compressor, together with the bearing housing in-between, form a compact unit. This unit is normally used as a turbocharger on turbocharged engines.

The air drawn in is injected into the light alloy spiral housing by the compressor wheel rotating at high speed (1) (60.000...125.000 rpm). Here the speed of the air is converted into pressure. The compressed air is further slowed down in the diffuser (8) and then fed to the combustion chamber (3). At the inlet to the combustion chamber, part of the air is drawn off and fed to the front of the combustion chamber pipe (3). This primary air is used as combustion air for the fuel. A turbulence generator (7) sets the air in rotation and slows it down such that fuel (propane) injected in gaseous form via the combustion nozzle (6) can burn with a stable flame.

The combustion pipe is cooled from outside by the secondary air. This is fed to the combustion chamber via holes (2) to cool the very hot combustion gases (approx. 2.000 °C) to the permitted turbine inlet temperature of 600...900 °C. An ignition plug (5) is used to ignite the air-fuel mixture on starting.

From the combustion chamber, the combustion gases flow into the spiral housing on the turbine and are accelerated for entry into the radial wheel (9). In the turbine, the gases give up their energy to the wheel to drive the compressor. During this process, the gases are expanded and cooled to a large degree. They leave turbine at around 700°C and can either be fed to the power turbine that follows, or to the thrust nozzle.



a	Exhaust gas outlet
b	Turbine wheel
c	Lubricating oil inlet
d	Plain bearing
e	Compressed air outlet
f	Shaft seal
g	Compressor wheel
h	Air inlet
i	Shaft
j	Lubricating oil outlet
k	Exhaust gas inlet

Fig. 3.6 Exhaust gas turbocharger

The turbine and compressor wheels are fitted to a common shaft (10) such that they are overhanging. The shaft is mounted in the bearing housing in plain bearings. Due to the very high speeds, the bearings have a floating intermediate sleeve.

The lubricating oil for the pressure lubrication is also used as a coolant for the bearings that are subjected to high temperatures.

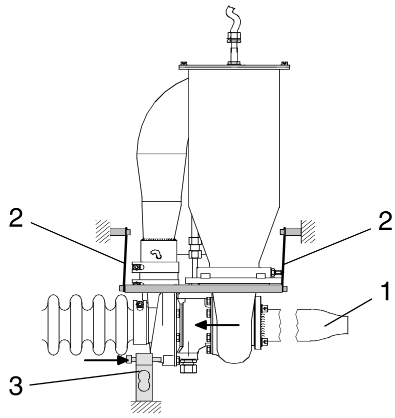
3.3.3 Power Turbine and Generator

A turbine from a turbocharger also serves as the power turbine. Instead of the compressor, here a belt drive is used to drive the generator. The highly reduction geared belt drive has a transmission ratio of 1:11 so that at a maximum turbine speed of 35.000 rpm, a generator speed of approx. 3.180 rpm is produced.

The power turbine is connected to the same oil circuit as the gas generator.

A three phase asynchronous motor is used as the generator. This is operated over synchronously, i.e. as a generator, using a frequency converter. The power generated is dissipated in resistors. At a turbine speed of 30.000 rpm, a power output of min. 1 kW can be generated.

3.3.4 Jet Pipe and Thrust Nozzle



1	Thrust nozzle
2	Leaf springs
3	Force sensor

Fig. 3.7 Thrust Measurement

In operation as a jet engine, the exhaust gases are expanded in the thrust nozzle (1) and, at the same time, accelerated. The gases exit freely from the jet nozzle. As the gas generator is mounted elastically on leaf springs (2), the thrust can be measured using an electrical force sensor (3).

3.3.5 Fuel System

Propane is used for the fuel. This has the advantage that in the case of ignition failure, no unburned fuel can collect in the system.

In addition, the low delivery pressure to the combustion chamber provides an effective self-regulating mechanism for the speed. With increasing speed, the pressure in the combustion chamber also increases. The lower pressure difference to the gas nozzle pressure automatically reduces the fuel feed. In this way the hazard normally present with gas turbines does not exist, and it is not necessary to use a complex speed regulator.

The main gas valve is fitted at the inlet of the gas to the system. After the main gas valve, the supply pressure is indicated. The rapid action stop valve shuts down the system immediately in the event of hazardous operating states. The nozzle pressure is adjusted using the pressure reducing valve. This is also indicated. The gas flow is indicated on a variable-area flowmeter. The regulator valve for the system power output then follows. From here the gas flows to the combustion chamber and is injected using a four-hole nozzle.

3.3.6 Lubricating System

The turbines place high requirements on the supply of lubricating oil. The oil collected in the lubricating oil tank is pumped through a primary oil filter and an oil cooler to the turbines by an electrically driven gear pump. A pressure limiting valve limits the oil pressure to max. 3 bar. An oil pressure switch interrupts the supply of gas for combustion as soon as the oil pressure drops below 1,5 bar. The oil temperature in the tank is indicated.

The feed of gas for combustion is also interrupted at more than 100 °C. The oil cooler is thermostatically regulated; the flow rate for the cooling water is regulated as a function of the oil temperature.

The return oil from the turbines runs back to the tank under gravity. Oil vapour produced is diverted to the intake and burnt in the gas turbine.

3.3.7 Starting and Ignition System

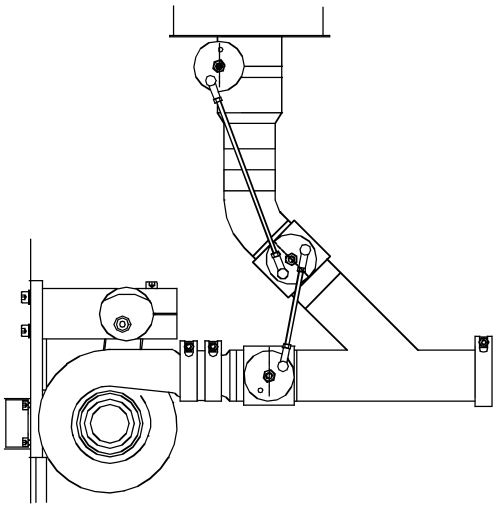


Fig. 3.8 Starting fan with flap arrangement

The starting system consists of a powerful fan and damper arrangement. On starting, the normal intake is closed using a damper and the connection to the starting fan opened. The damper arrangement is operated using a rotary knob on the front panel. The starting fan replaces the compressor, which on starting does not yet function, and provides the air necessary for initial combustion. Once the turbine has reached a certain minimum speed, the compressor takes over the function and the starting fan can be switched off.

The ignition system consists of an ignition plug and an ignition transformer for the necessary ignition voltage. The ignition system is operated using a push button. At the same time, the feed of gas for combustion is enabled via the rapid action stop valve. The ignition system must be operated until ignition has occurred in the combustion chamber. This is indicated by increasing turbine inlet temperature. At more than 500°C, the gas feed remains enabled and the ignition can be switched off.

3.4 Setting Up the Gas Turbine

3.4.1 Operation with Power Turbine

Due to its large requirement for fresh air (approx. 300 m^3/h) the gas turbine is only permitted to be operated in **large, well ventilated rooms**. It must be possible to feed an **exhaust pipe** to the outside. An exhaust pipe longer than 5 m is to be avoided due to the high pressure loss. At longer pipes the cross section is to be enlarged or a suction blower is to be used.

Due to the low noise level of the turbine (80dB/1m), special noise attenuation measures are generally not necessary.

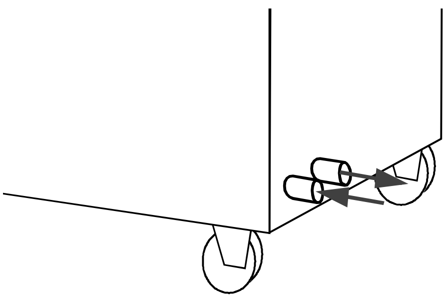


Fig. 3.9 Cooling water connection

- Position gas turbine on a flat surface and secure against rolling away by operating the brakes on the castors.

  To provide space for access for maintenance and servicing tasks, a free space of min. 1 m should be left behind the gas turbine.

- Connect **cooling water connections** as per Fig. 3.9.

- Connect **exhaust pipe** to draw the exhaust gases to the outside.

  Exhaust pipe must be temperature resistant. Exhaust gases have a temperature of up to **700 °C**.

  If there is a risk of contact, the exhaust pipe is to be protected with a grille.

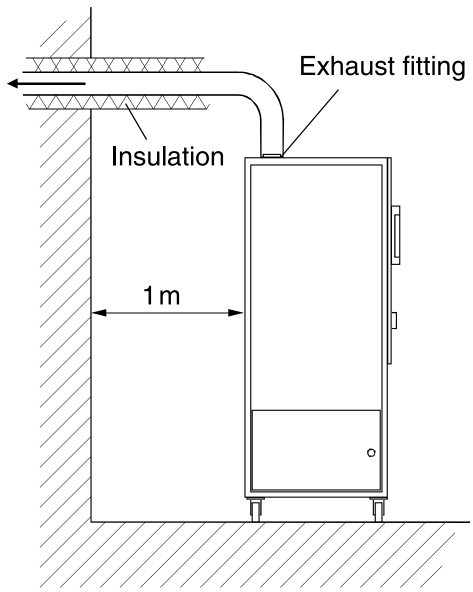


Fig. 3.10 Distance to the wall and exhaust pipe

If radiated heat is considered undesirable, the exhaust pipe must be insulated with temperature resistant insulation.

It is imperative that contact of the exhaust **pipe with flammable material is avoided.** Do not use any brackets or seals made of plastic.

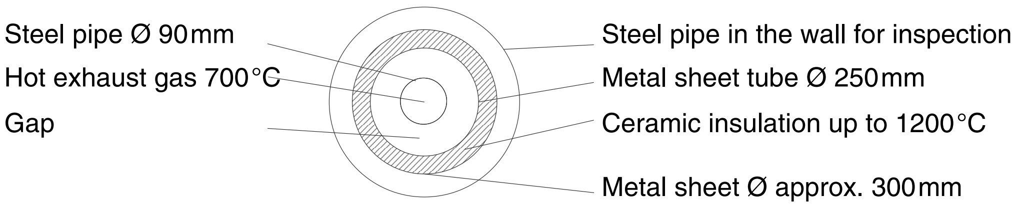


Fig. 3.11 Cross-section of the exhaust gas pipe

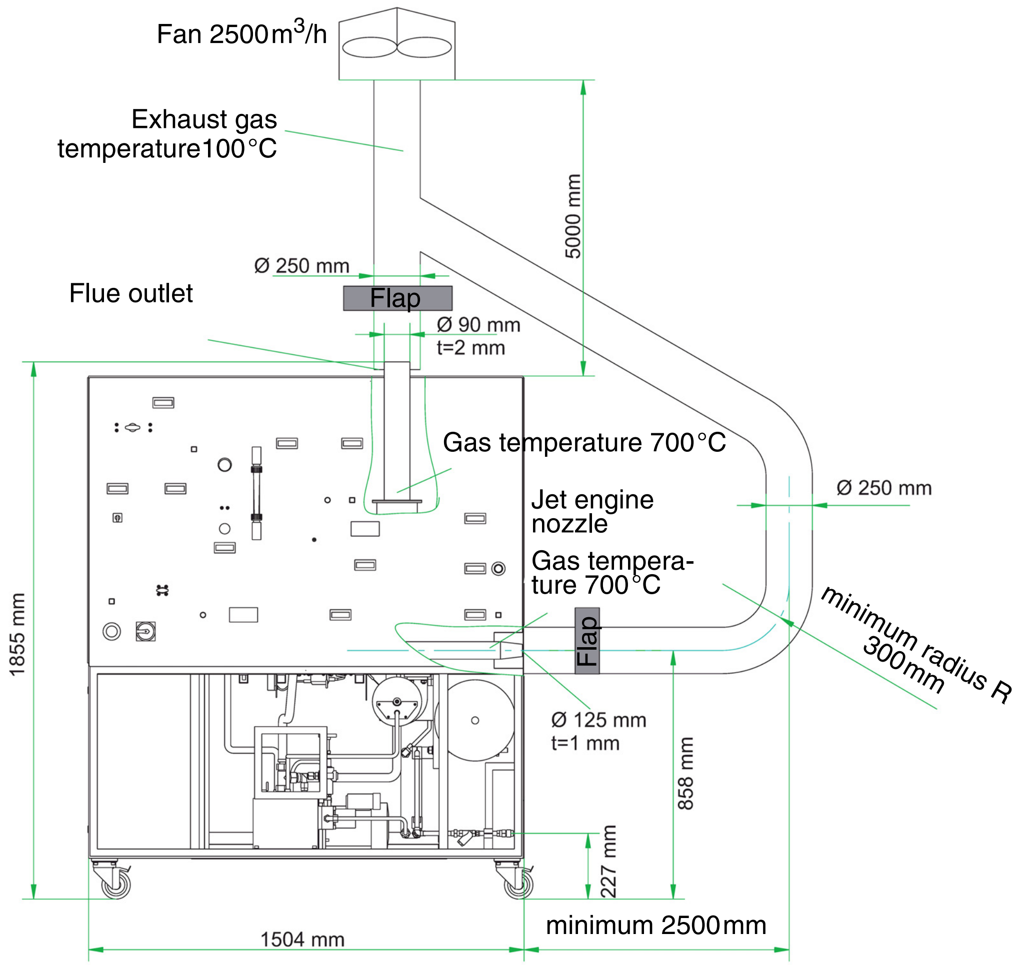


Fig. 3.12 Suction device ET 792 – front view

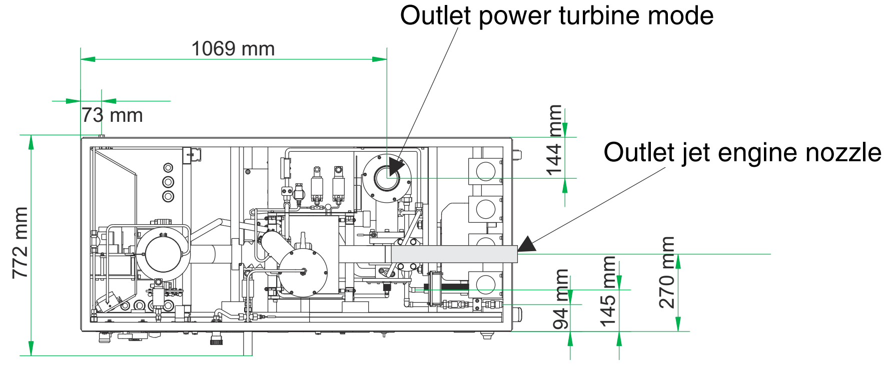


Fig. 3.13 Suction device ET 792 – top view

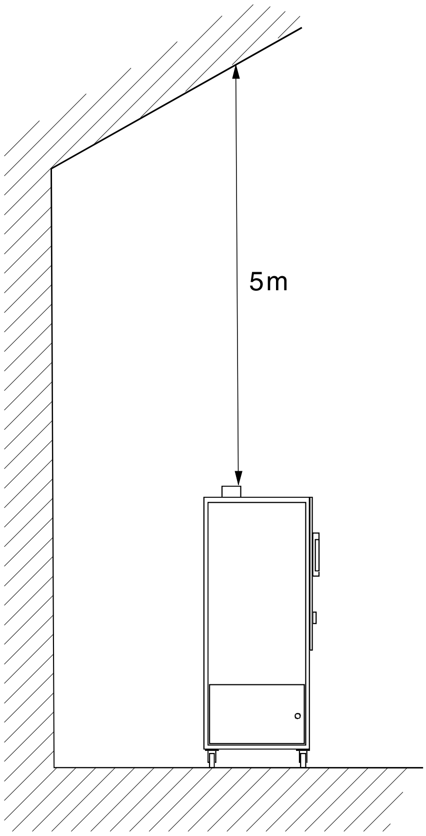


Fig. 3.14 Distance to the ceiling

- In open, very well ventilated halls with a ceiling height of more than 7m it is also possible to work without the exhaust pipe.

  Here is imperative to ensure that **in the area** of the exhaust jet there is no flammable material.

- An approved and tested **fire extinguisher** with a min. capacity of 6kg is to be placed in the immediate vicinity of the gas turbine.

NOTICE

The gas connection must be made and checked by a qualified gas fitter.

- Connect propane gas bottle using the hose supplied. Recommended bottle size min. 33kg. The **propane gas bottle is to be placed in a well ventilated room** (preferably outside). Gas turbine and propane gas bottle should, if possible, be in separate rooms.

NOTICE

At low ambient temperatures, the gas that can be supplied by the propane gas bottle drops and with it the power output of the gas turbine. It may then be necessary to connect two propane gas bottles in parallel.

- Connect **electrical supply**.

3.4.2 Operation as Jet Engine

⚠ WARNING

During operation as jet engine a very high noise level is generated (< 110dB(A)).

Risk of hearing damage.

- Wear suitable ear protection during operation.

The following points, different to operation as a power turbine, are to be observed.

On the jet turbine the exhaust jet leaves the turbine horizontally at very high speed and temperature.

- An area of 5m in the direction of the jet and 1...1,5m to the sides is to be fenced off.
- Within a distance of 10m in the direction of the jet, there must be no objects sensitive to heat or flammable materials.
- The exhaust jet should be directed to the outside through a window or doorway if possible. An exhaust pipe can be connected to the existing guide fitting. In certain circumstances, however, a loss in power output must be expected.

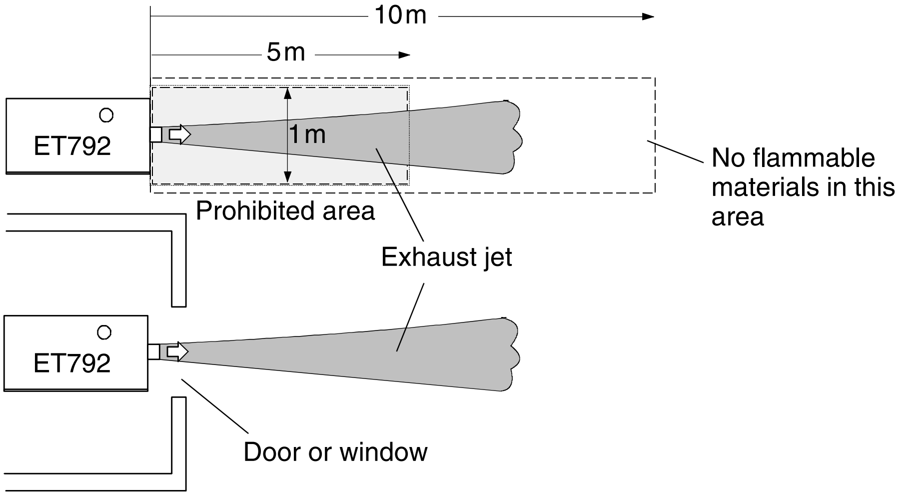


Fig. 3.15 Safety zones at the jet outlet

3.4.3 Initial Check of the Gas Turbine

Before the turbine is operated the first time, it must be checked for transportation damages and disadjustments.

If a special G.U.N.T. training is ordered this check will be done by G.U.N.T.

- Remove all trim panels to get free access to all components of the gas turbine.

WARNING

Risk of burns at hot unit components.

- Leave the unit cool down before touching.

3.4.3.1 Checking the Screws for Tight Fit

Check all screws. Especially check following screws:

- Mounting screws (2 x M12) of the power turbine mounting plate located behind the generator.
- Screws of the connection pipe between gas generator exhaust and inlet power turbine.
- Mounting screws of the exhaust pipe and the muffler.
- Screws of generator base plate.
- Screws of the starting flaps linkage.
- Screws of the combustion chamber cover.

3.4.3.2 Checking the Starting Flaps

The actual position of the flaps are indicated by flattenings at the axles.

- Set the starting flaps to start position.

  The lower flap must be in a horizontal position, the upper flap must be under 90° to the duct.

- Set the starting flaps to run position.

  The upper flap must be in alignment to the duct, the position of the lower flap must be under 90° to the duct.

If the position is not perfect, the linkage must be adjusted. After adjustment tighten the nuts carefully.

3.4.3.3 Checking the Tension of the Belt Drive

The tension of the belt drive to the generator must be checked very carefully. If the tension is to hard, the bearings of the power turbine shaft can be damaged. If the belt drive tension is to low, the belt may slip during high performance.

The belt should have a free play at the mid of the span of about 10...20 mm. For test load the belt only by the finger tip.

⚠ WARNING

Testing and adjusting the belt during operation causes severe hand injuries.

- To test and adjust the slackness of the belt, first shut down the gas turbine and then shut down the entire unit using the main switch and the emergency stop mechanism.

If the turbine is running the belt should run without excessive flutter or unusual noise.

Adjusting the belt tension

- Loose the knurled screw and open the side door with the Grid.
- Loose the 4 securing screws (across flats 13) at the wheel side of the generator base.
- Adjust the tension by the straining screw (across flats 17).
- After adjustment tighten the securing screws carefully.

3.4.3.4 Check if the Gas Pipes are Tight

NOTICE

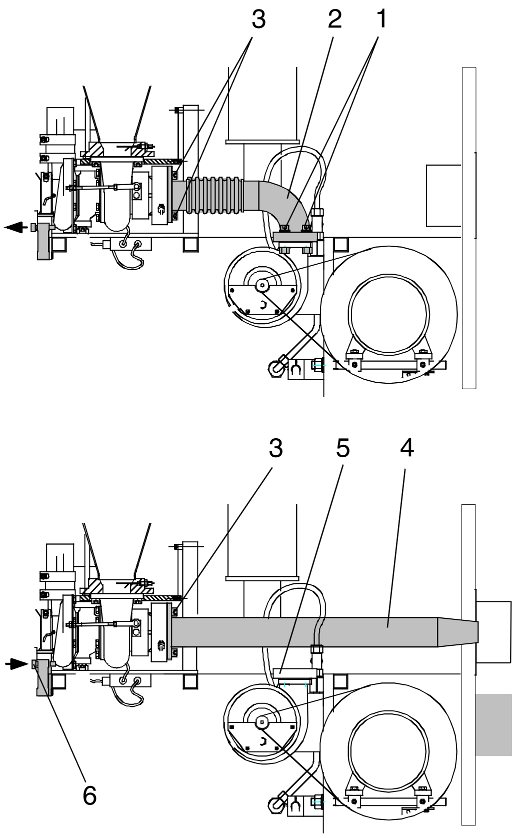
After connection to the gas bottle and before opening the main gas valve and rapid action stop valve check all joints for leakage. This should be done by a qualified gas fitter.

3.4.4 Conversion to Thrust Mode (Jet Engine)

⚠ WARNING

Risk of burns at hot unit components.

- Leave the unit cool down before touching.



1	Screws
2	Connecting pipe
3	Hexagon socket head screws
4	Nozzle pipe
5	Flange
6	Follower

Fig. 3.16 Conversion to thrust mode

- Remove rear trim panel.
- Undo four screws (1) on the joint power turbine / connecting pipe. Store the nuts and screws.
- Undo three hexagon socket head bolts (3) on the joint gas generator / connecting pipe with an 8mm hexagon wrench.
- Remove connecting pipe (2).
- Mount the cover on the flange (5).
- Place nozzle pipe (4) on the gas generator and tighten evenly with three hexagon socket head bolts (3). To avoid the bolts seizing with the heat, they are to be smeared with copper paste.
- Remove transport secure devices (red painted).
- Undo follower (6) on the force sensor until it is in gentle contact with the compressor housing. The thrust indicator should indicate light pre-tensioning (1...2N). Tighten lock nut.

NOTICE

Do not run up the power turbine for generator load using the potentiometer.

Conversion to power turbine operation is performed in the reverse order.

- Important! First screw in the follower (6) on the force sensor so that there is 5...10mm play between the bolt and compressor housing.
- Fit the connecting pipe (2).

3.5 Operation of the Gas Turbine

3.5.1 Starting Preparations

Before starting the gas turbine, the following tasks are to be carried out:

- Check oil level.

  For this purpose remove the rear trim panel and check the oil level in the oil tank using the dip stick.

  If the oil level is too low, add appropriate oil. Do not overfill the oil tank.

  Close rear trim panel again.

- Open propane gas bottle valve.

NOTICE
The gas connection must be checked for leaks by a qualified gas fitter.

- Open cooling water connection. During operation the cooling water discharge must be free at an oil temperature above 60 °C.

  Cooling water flow rate 3...5 ltr / min.

- Set potentiometer for generator load to zero.
- Switch on master switch.
- Check function of the temperature and speed displays.
- Open main valve and check gas supply pressure. Depending on the temperature of the gas bottle, the pressure should be between 3 bar and 15 bar.

The gas turbine is now ready for use.

3.5.2 Starting the Gas Turbine

The gas turbine is started by following a set procedure. This is typical for all gas turbines. Differences only arise due to variations in the degree of automation. In Fig. 3.17 the procedure is shown schematically over time.

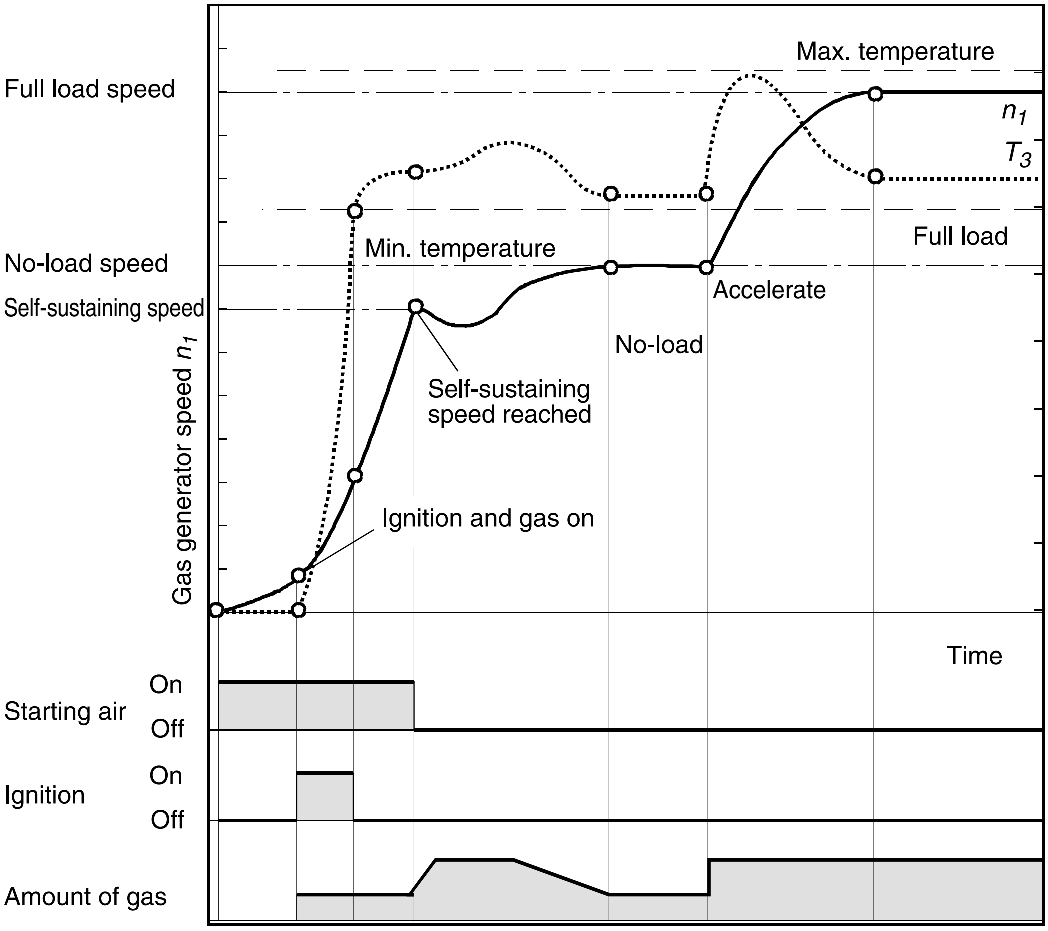


Fig. 3.17 Start-up procedure

It is desirable to carefully read through and digest the description of the starting procedure prior to the performance of the experiment.

As during starting an eye must be kept on several processes at once, for the inexperienced it is better to perform the starting procedure with two people.

The labels for the controls relate to Fig. 3.3, Page 15.

- Set potentiometer for generator load (9) to zero.
- Close gas regulator valve (4).
- Change-over damper (8) for **starting air** to **On**.

NOTICE

Oil vapour discharge from oil tank

Due to the nature of the system, whitish oil vapour escapes from the oil tank during starting fan operation when the oil is warm.

- Switch on starting fan (7).
  - Oil pressure indicator lamp (19) illuminates.
  - Gas generator speed n_1 (24) increases.
  - Combustion chamber is vented.
- **Only with power turbine operation**:
  With potentiometer for generator load (9), bring the power turbine to around 10.000...12.000 rpm. In this way the power turbine is evenly warmed up and the generator protected.
- After around 10 s, operate **ignition button** (6).

  At the same time, slowly increase the gas flow (18) with gas regulator valve (4) until ignition occurs (T_3 increases).

- Following ignition, leave the ignition button pressed until the turbine inlet temperature rises to more than T_3 = 500°CC (22). The ignition button (6) can then be released.

  Indicator lamps (20) and (5) illuminate.

  If the ignition button is released below 500°, the gas rapid action stop valve assumes that the ignition was not successful and closes. The starting procedure must then be repeated. Prior to renewed ignition, the combustion chamber should to be vented for approx. 10s.

- Run up turbine to **self-sustaining speed of n_1 = 70.000 rpm**. Doing so, adjust the gas flow rate such that the turbine inlet temperature T_3 is max. 1.000°C.

- At a speed of **n_1 = 70.000 rpm,** set starting air damper to **Off**. If the speed falls sharply and the turbine threatens to stall, the gas feed was too low. In this case open the starting damper again and accelerate back to 70.000 rpm with slightly increased gas feed.

NOTICE

If the starting air is shut off at a speed of less than 70.000 rpm, the turbine cannot be run up even with a very large gas feed. There is a risk of overheating (T_3 > 1.000°C).

- By regulating the gas feed, adjust the speed of the turbine to a **no-load speed of around n_1 = 80.000 rpm**.

- Switch off starting fan.

3.5.3 Operation of the Gas Turbine

NOTICE
Do not operate the gas turbine unsupervised.

From time to time, the displays for supply pressure, speed, turbine inlet temperature and oil temperature are to be checked.

If the following limits are exceeded, the gas turbine is **automatically shut down**:

- Gas generator speed n_1 > 125.000 rpm
- Turbine inlet temperature T_3 > 1.000 °C
- Oil temperature T_{oil} > 100 °C

Once the turbine is warm, the no-load speed can be reduced to 60.000...70.000 rpm.

The full load speed should not exceed 120.000 rpm.

If 120.000 rpm cannot be reached despite fully opened gas valve, nozzle pressure (13) should be increased using the gas pressure regulator (3).

NOTICE
If the turbine is in jet mode, the power turbine may not be run up. The potentiometer for generator load (9) must be set to zero.

3.5.3.1 Loading the Power Turbine

The power turbine is loaded using an asynchronous generator. Using potentiometer for generator load (9) a **target speed for the generator** is set.

If the **target speed is below** the turbine no-load speed, the **power turbine is braked** and the generator outputs the power to the braking resistors.

If the **target speed is above** the turbine no-load speed, the generator acts as a motor and the **power turbine is driven**.

In **generator mode** the current electrical power P_{el} can be read on the power display (27).

In **motor mode** the display indicates **zero**.

The speed n_2 of the power turbine can be read on the display (26).

Due to the need for lubrication, motor operation is only possible with the oil pump running (turbine or starting fan running).

NOTICE

A maximum power output of 1,5 kW at 30.000 rpm may be exceeded only for short periods ($t < 1$ min).

(The continuous power output according to DIN 6271A is 1,25 kW. This power output can be exceeded by 20 % for 0,5 h/12 h).

3.5.4 Shutting Down the Gas Turbine

The gas turbine is shut down by shutting off the gas feed.

- Trigger the **rapid action shut down** via button (5).

  The gas rapid action stop valve switches off, the burning at the combustion chamber ends and the turbine stops.

  To cool the turbine bearings, the oil pump runs on for approx. 60s.

- Set potentiometer for generator load (9) of the power turbine to zero.

NOTICE

Oil vapour discharge from oil tank

Due to the nature of the system, whitish oil vapour escapes from the oil tank during starting fan operation when the oil is warm.

- To **post cool** the hot turbine, it is sensible to switch on the starting air fan (7) and open the starting air damper (8) immediately after shut down.

  As the turbine can turn, the oil pump is automatically placed in operation.

  A post cooling period of 2...3min is sufficient.

- Close main gas valve (2) and switch off the unit with the master switch (10).

3.5.5 Faults and Fault Rectification

This section describes problems that may arise and their causes.

Gas turbine does not start	
No reaction on pressing the ignition button.	• No oil pressure or oil temperature too high.
No ignition, T_3 too low, rapid action stop valve de-energised after release of the ignition button, red indicator lamp (5) off.	• Ignition button not pressed long enough. • Starting fan not on and/or dampers for starting air not open. • No gas supply pressure. • Nozzle pressure too low (min. 2bar). • Gas flow rate too low. • Ignition plug defective or ignition cable fallen off. • Ignition plug spark gap too small, increase gap to max. 1,2mm.
T_3 increases, turbine does not come up to speed.	• Starting fan not at full speed. • Starting air damper not fully open. • Gas flow rate too low, carefully increase amount of gas, T_3 must not exceed 1.000°C. • Oil temperature too low, let oil pump run until temperature reaches min. 20°C.
After shut down of the starting air the speed drops again.	• Starting air is shut off too early, min. speed 70.000rpm. • Not enough gas, carefully increase amount of gas, T_3 must not exceed 1.000°C.

Gas turbine slowly looses speed	
T_3 drops, insufficient gas.	• Insufficient gas flow. • Insufficient nozzle pressure. • Insufficient supply pressure, gas bottle empty.
T_3 increases, insufficient air.	• Damper for starting air not fully at off. • Intake system clogged. • Exhaust system clogged, counterpressure too high.

Tab. 3.1 Fault and fault rectification

Gas turbine switches off and looses speed rapidly	
Rapid action stop valve de-energises, red indicator lamp (5) off (safety shut down).	• T_3 too high (more than 1.000 °C). • T_3 too low (less than 500 °C), flame out, no gas. • Oil temperature too high (more than 100°C), no or insufficient cooling, insufficient oil in the tank. • Insufficient oil pressure, oil tank empty (oil pressure indicator off). • Gas generator speed too high (more than 125.000 rpm). • Power supply failure (all displays off).

Gas generator speed indicator indicates inconsistent values	
Gas generator speed indicator fluctuates and / or indicates values that are too low.	• Sensor head on the optical speed sensor is dirty. – Remove sensor head from the compressor housing and clean. • Adjust sensitivity of the sensor at the sensor housing

Tab. 3.1 Fault and fault rectification

3.6 Maintenance

3.6.1 Lubricating Oil

- Prior to each use, the oil level in the oil tank is to be checked with the dip stick. If necessary add oil (do not overfill).
- The oil and the oil filter are to be replaced every 200 operating hours or every four years.

3.6.2 Ignition Plug

In case of starting problems, the ignition plug is to be checked for damage or soiling.

- Remove rear trim panel.
- Remove ignition cable on the ignition plug.
- Unscrew ignition plug with 16mm plug spanner.
- The spark gap should be between 0,8mm and 1,0mm.

⚠ WARNING

Risk of burns at hot unit components.

- Leave the unit cool down before assembly and disassembly of the ignition plug.

3.7 PC Measurement Data Acquisition

3.7.1 Installation of the Software

The following is needed for the installation:

- A fully operational PC with USB port (for minimum requirements see Chapter 6, Page 67).
- G.U.N.T. CD-ROM.

  All components necessary to install and run the software are contained on the CD-ROM delivered by G.U.N.T.

Installation Routine

NOTICE
The trainer must be connected to the PC's USB port before installation of the software.

- Boot the PC.
- Load the G.U.N.T. CD-ROM.
- From the “Installer” folder, launch the “**Setup.exe**” installation program.
- Follow the installation procedure onscreen.
- After starting, the installation runs automatically. During the course of the installation, various software components are loaded onto the PC:
  - Software for PC-data acquisition
  - Driver routines for the „LabJack®“ USB converter
- Reboot the PC after installation is finished.

3.7.2 Operating the Software

Fig. 3.18 Language selection

- Select and start the program by choosing: **Start / All Programs / G.U.N.T. / ET 792.**
- When the software is run for the first time after installation, the language to be used for the software is requested.

  The language selected can subsequently be changed at any time on the "**Language**" menu.
- Various pull-down menus are provided for additional functions.
- For detailed instructions on use of the software refer to its Help function. This **Help function** is accessed by opening the pull-down menu **„?"** and choosing **„Help"**.

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.

4.1 The Open Gas Turbine Process

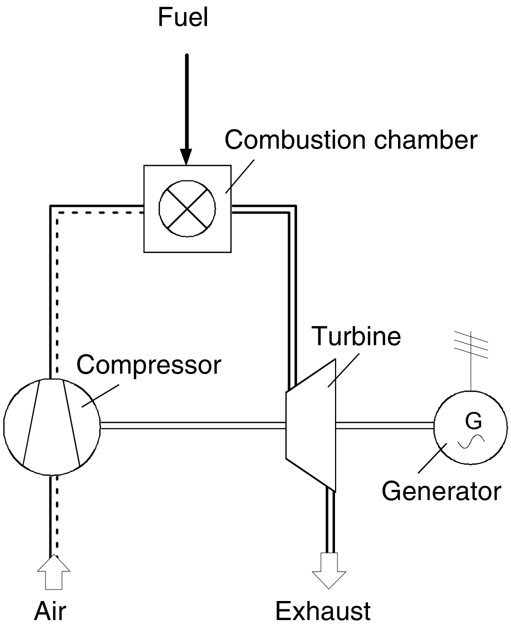


Fig. 4.1 Simple open gas turbine plant

The functional gas turbine model uses an open **circulatory process** in which the working medium is extracted from the surrounding environment and later returned to it.

During this process the working medium, air, is subjected to the following changes of state:

- **Adiabatic compression** of the cold air, using a compressor, from ambient pressure p_1 to pressure p_2 and the associated in increase in temperature from T_1 to T_2.
- **Isobaric heating** of the air from T_2 to T_3 through the addition of heat. Heat is added by burning fuel with the oxygen from the air in the combustion chamber.
- **Adiabatic expansion** of the hot air in a turbine from pressure p_2 to p_1 with a temperature drop from T_3 to T_4.

In a closed circulatory process the working medium would need to be isobarically cooled back down to the inlet temperature T_2. With an open circulatory process the residual heat is also given off to the surrounding environment.

The **mechanical power** extracted using the turbine is partly used to drive the compressor, and is partly available as useful power. This power can be utilised, for example, to operate a generator.

4.1.1 Depiction on the Total Heat-Entropy Diagram

To be able to better evaluate the relationships in the circulatory process, it is useful to depict the process on a total heat-entropy diagram, the so-called *T,s* diagram. On this diagram the temperature of the working medium is plotted against the specific entropy.

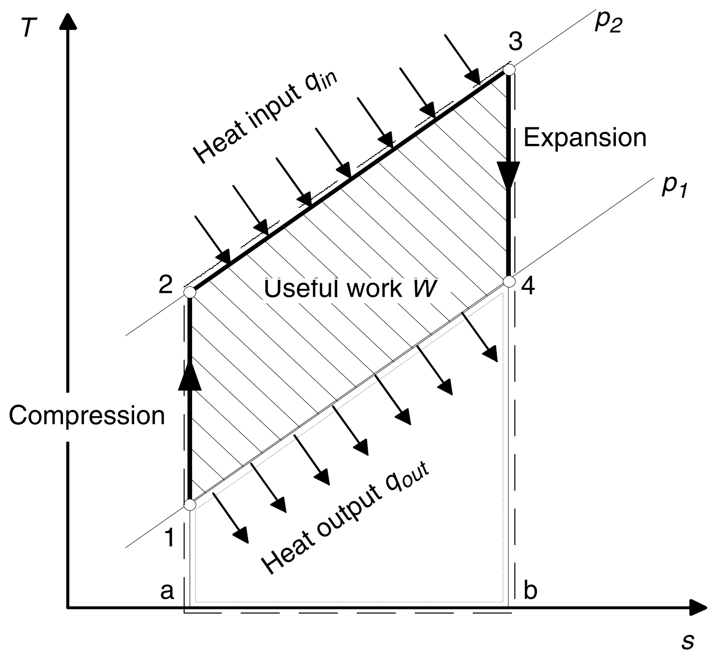


Fig. 4.2 *T,s* diagram of the gas turbine process

On the *T,s* diagram, the amounts of heat can be depicted as areas. The useful work is given by the difference between the amount of heat supplied, the area a,2,3,b, and the amount of heat drawn off, area 4,b,a,1.

Using the *T,s* diagram, questions on the thermal efficiency and capacity of the process to perform work can be investigated. Both the temperature ratios and the pressure ratio $\Pi = \frac{p_2}{p_1}$ are significant here.

4.1.1.1 Thermal Efficiency

The thermal efficiency is given by the relationship of the heat supplied to the mechanical work. Assuming that the working medium has a constant capacity to perform work, the thermal efficiency is given by:

$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\Pi \cdot \frac{\kappa - 1}{\kappa}} \tag{4.1}$$

With an average value for $\kappa = 1{,}4$ this equation yields:

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

It can be seen that the efficiency is only dependent on the pressure ratio Π. The highest temperature in the process, the turbine inlet pressure T_3 does not have any influence on the thermal efficiency.

4.1.1.2 Specific Capacity to Perform Work

The following relationship applies for the specific capacity to perform work:

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

It can be seen that, apart from the pressure ratio, the intake and turbine inlet temperature are of significance. The intake temperature is generally determined by the ambient conditions. The turbine inlet temperature T_3 should be selected such that it is as high as possible. In practice it is limited by the thermal stability of the turbine blades. Thus the pressure ratio Π is also in this case the decisive factor.

The **power output** of the plant is given by multiplying the specific capacity to perform work with the mass flow rate used.

$$P_N = \dot{m} \cdot w_N \quad (4.4)$$

The relationships given here are applicable to a single shaft plant, they are thus not directly applicable to our gas turbine. However they do give general pointers for understanding the operating behaviour of the plant. For example, the pressure ratio is a function of the square of the speed. Thus the plant is significantly more efficient at high speeds.

4.1.1.3 Depiction on the *p,v* diagram

The circulatory process can also be depicted on a *p,v* diagram. Here especially the compression and expansion process are clearly depicted.

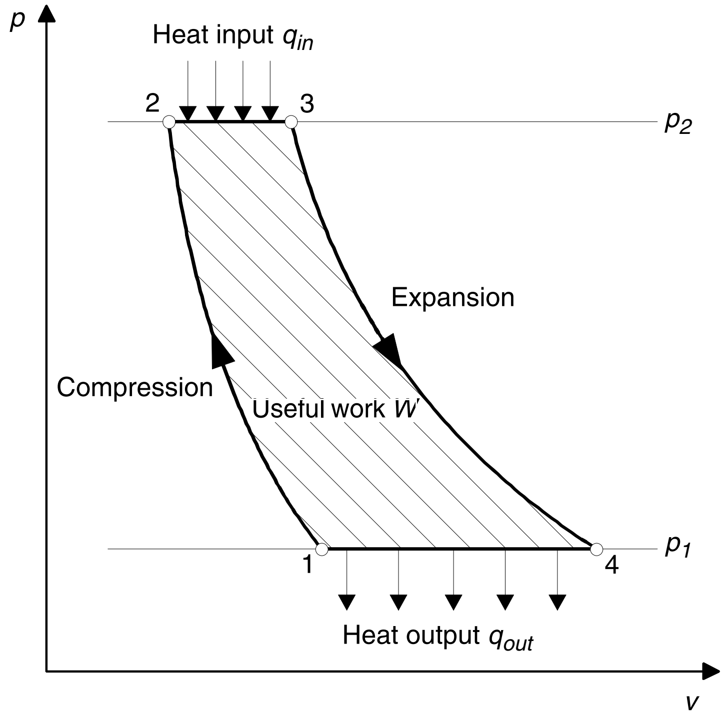


Fig. 4.3 *p,v* diagram of the gas turbine process

Mechanical work also results in a closed area here. Contrary to the *T,s* diagram, in this case the areas depict the mechanical work. It can be seen that on the supply of heat between 2 and 3, the specific volume of the gas increases, that is the density reduces. The excess useful power of the turbine results from it being able to process a higher volume for the same pressure difference as on the compressor.

4.1.2 2-Shaft Plant

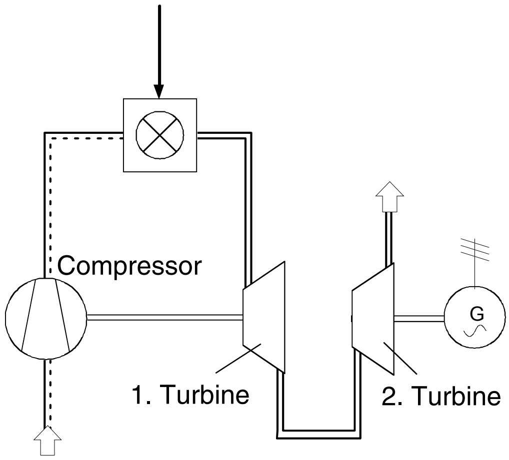


Fig. 4.4 2-shaft gas turbine plant

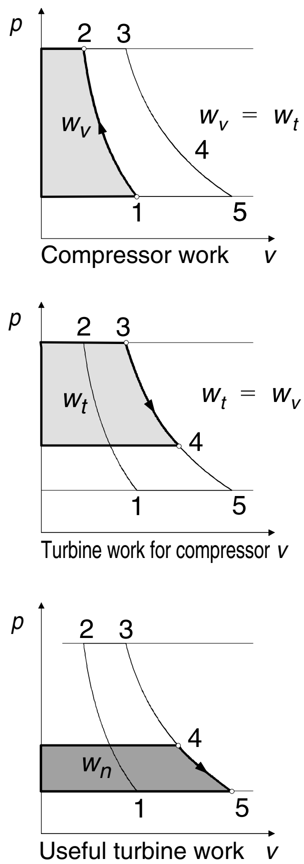


Fig. 4.5 *p,v* diagram of a 2-shaft plant

A **2-shaft plant** has two independent turbines. The first turbine only drives the compressor. As the entire pressure drop available is not needed for this process, there is enough energy for a second turbine connected in series. This second turbine, also termed the **power turbine**, generates the useful power.

The advantage of this arrangement is that a change in the load or the speed of the power turbine has little or no effect on the compressor and the compressor continues to run at the optimal speed in the best efficiency region. Even the jamming of the power turbine cannot cause damage to the plant. In addition the speed of the drive can be better matched. For this reason, 2-shaft plants are preferred for vehicle and ship drives with widely varying load and speed requirements.

As the first turbine together with the compressor and the combustion chamber only generates the working gas for the power turbine, this group of components is also called the **gas generator**.

For a 2-shaft plant the ***p,v* diagrams** at Fig. 4.5 are applicable.

The compressor turbine only needs to raise the power demanded by the compressor. This results in the area w_V being the same as w_T. As the specific volume v is larger than on the compressor, the compressor turbine requires a smaller pressure drop to point 4. This results in the working gas not being expanded all the way to pressure p_1. The remaining pressure drop to point 5 can then be used in the power turbine and converted into the useful work w_N.

As appropriate to their pressure regions, a differentiation is also made between the turbines in the form of high pressure (HP) and low pressure turbines (LP).

4.1.3 Gas Turbine as Jet Engine

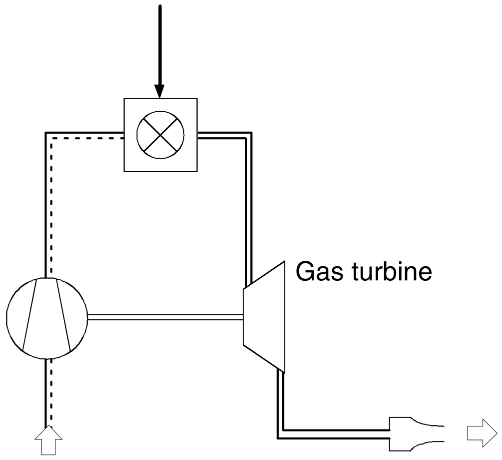


Fig. 4.6 Jet engine

For aircraft propulsion systems, from a certain aircraft speed it is better to use the exhaust jet directly for the generation of thrust. The simplest jet engine consists of single shaft gas turbine in the open process. The only partially exploited exhaust gases, which still contain energy, are accelerated in a thrust nozzle and generate the momentum necessary for the propulsion of the aircraft. In an optimal nozzle configuration, the exhaust gases are expanded down to ambient pressure. In this situation the nozzle takes over the task of the power turbine.

The thrust can be calculated straightforwardly using the principle of linear momentum from the mass flow rate achieved $\dot{m}$ and the speed at inlet (c_1) and outlet (c_2):

$$S = \dot{m} \cdot (c_2 - c_1) \tag{4.5}$$

Here it is to be noted that the thrust is a vectorial parameter and only makes a contribution to speed components in the direction of the thrust.

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.

The following analyses refer to experiment No. 5. In several cases concerning load points, the analyses refer to experiments No. 1, 2 and 3. The evaluation of thrust refers to experiment No. 4.

5.1 Recording Measured Values

The measured values should only be read with the turbine in a steady state. The following measuring values are exemplary and subject to large variations due to ambient conditions etc.

Experiment No.:	1	2	3	4	5	6
Gas T_G in °C	9,5	10,9	11,3	14,9	17,6	
Gas nozzle p_D in bar relative	0,86	1,10	1,34	1,16	1,03	
Compressor inlet T_1 in °C	18,6	12,5	13,4	9,0	27,6	
Compressor outlet T_2 in °C	86	101	118	83	93,4	
Combustion chamber pressure loss p_2-p_3 in mbar	10,3	12,8	15,3	14,7	14,3	
Turbine inlet T_3 in °C	785	830	857	840	898	
Turbine inlet p_3 in bar relative	0,71	0,90	1,12	0,94	0,71	
Turbine inlet p_3 in bar	1,73	1,92	2,14	1,96	1,729	
Power turbine inlet T_4 in °C	578	603	624	600	763	
Power turbine inlet p_4 in mbar relative	143	189	229	112	216	
Power turbine inlet p_4 in bar	1,163	1,209	1,249	1,132	1,229	
Power turbine outlet T_5 in °C	538	557	584	-	694	
Air flow rate in ltr/s	77	87	98	100	90,3	
Air flow rate $\dot{m}_a$ in kg/s	0,093	0,108	0,121	0,125	0,106	
Gas flow rate in kg/h (2 bar; 0 °C)	5,2	6,0	6,6	6,2	5,7	
Gas flow rate $\dot{m}_G$ in g/s	1,37	1,68	1,95	1,75	1,5	
Speed n_1 in 1/min	99.000	110.000	120.000	116.000	101.400	
Speed n_2 in 1/min	30.000	30.000	30.000	-	24.400	
Electrical power P_{el} in W	909	1.420	1.697	-	1.683	
Thrust S in N	-	-	-	35	-	
Oil temperature T_{oil} in °C	47	50	57	50	62	
Comment	Useful power	Useful power	Useful power	Thrust	Useful power	

Tab. 5.1 Gas turbine experiment

Date: 17.03.00
Ambient temperature in °C: 7
Air pressure in bar: 1,020
Relative humidity in %: 40

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

$$\dot{m}_a = \frac{\rho_o}{1.000} \cdot \frac{T_o p_1}{p_o(T_1 + 273)} \cdot \text{display}\left(\frac{ltr}{s}\right) \qquad (5.1)$$

with

$\rho_o = 1{,}199\ kg/m^3$

$T_o = 293\ K$

$p_o = 1{,}013\ bar$

$$\dot{m}_a = 0{,}347\frac{kg}{m} \cdot \frac{p_1}{(T_1 + 273)} \cdot \text{display}\left(\frac{ltr}{s}\right) \qquad (5.2)$$

Here T_1 is the intake temperature in °C and p_1 the ambient pressure in bar.

The **gas mass flow** $\dot{m}_G$ in $\frac{g}{s}$ is calculated as follows:

$$\dot{m}_G = \frac{1.000}{3.600} \cdot \sqrt{\frac{273 + T_0}{273 + T_G}} \cdot \sqrt{\frac{p_D}{p_0}} \cdot \text{display}\left(\frac{kg}{h}\right) \qquad (5.3)$$

with

$T_0 = 0°C$ $\qquad TG = 10°C$

$p_o = 2\,bar\ abs.$ $\qquad pD = 2{,}3\,bar\ abs.$

$$\dot{m}_G = 0{,}295 \cdot \text{display}\left(\frac{kg}{h}\right)$$

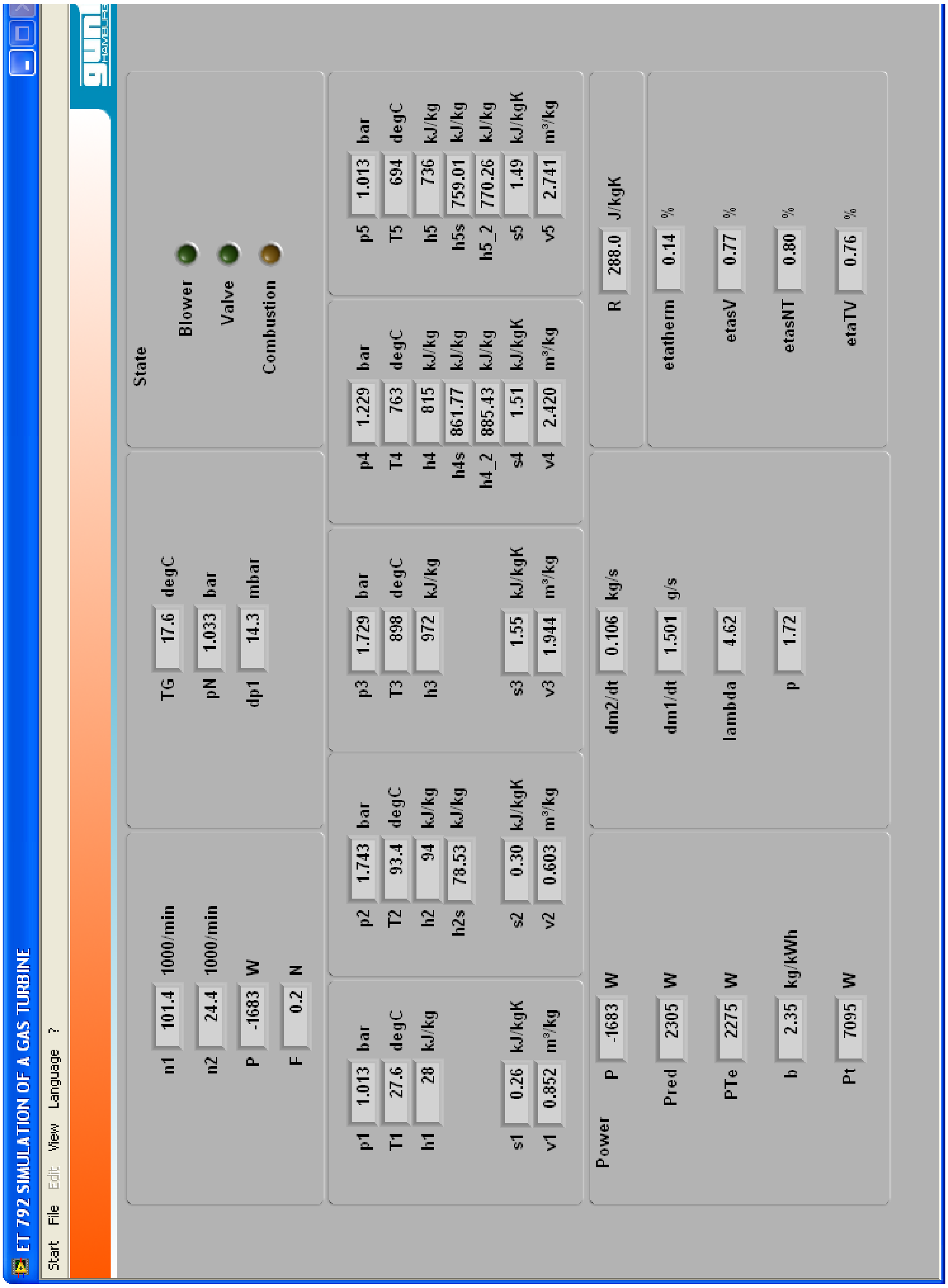


Fig. 5.1 Measured values

5.2 Determination of the Operating Point of the Compressor

The operating point of a compressor is characterised by air flow rate $\dot{m}_a$ and pressure ratio Π. The air flow rate $\dot{m}_a$ was calculated in Chapter 5.1.

The pressure ratio Π is calculated from the ratio of the intake pressure p_1 and outlet pressure p_2.

$$\Pi = \frac{p_2}{p_1} \tag{5.4}$$

The outlet pressure must be calculated from the turbine inlet pressure and combustion chamber pressure difference:

$$p_2 = p_3 - (p_3 - p_2) \tag{5.5}$$

This yields the following values for the three load points:

Load point	Air flow rate $\dot{m}_a$ in kg/s	Outlet pressure p_2 in bar	Pressure ratio Π
1	0,093	1,72	1,68
2	0,108	1,91	1,87
3	0,121	2,12	2,08

Tab. 5.2 Evaluation of Experiment

By plotting the operating points on the compressor map, it can be assessed whether the compressor is optimally designed. Of particular interest are the efficiency and distance from the pump limit.

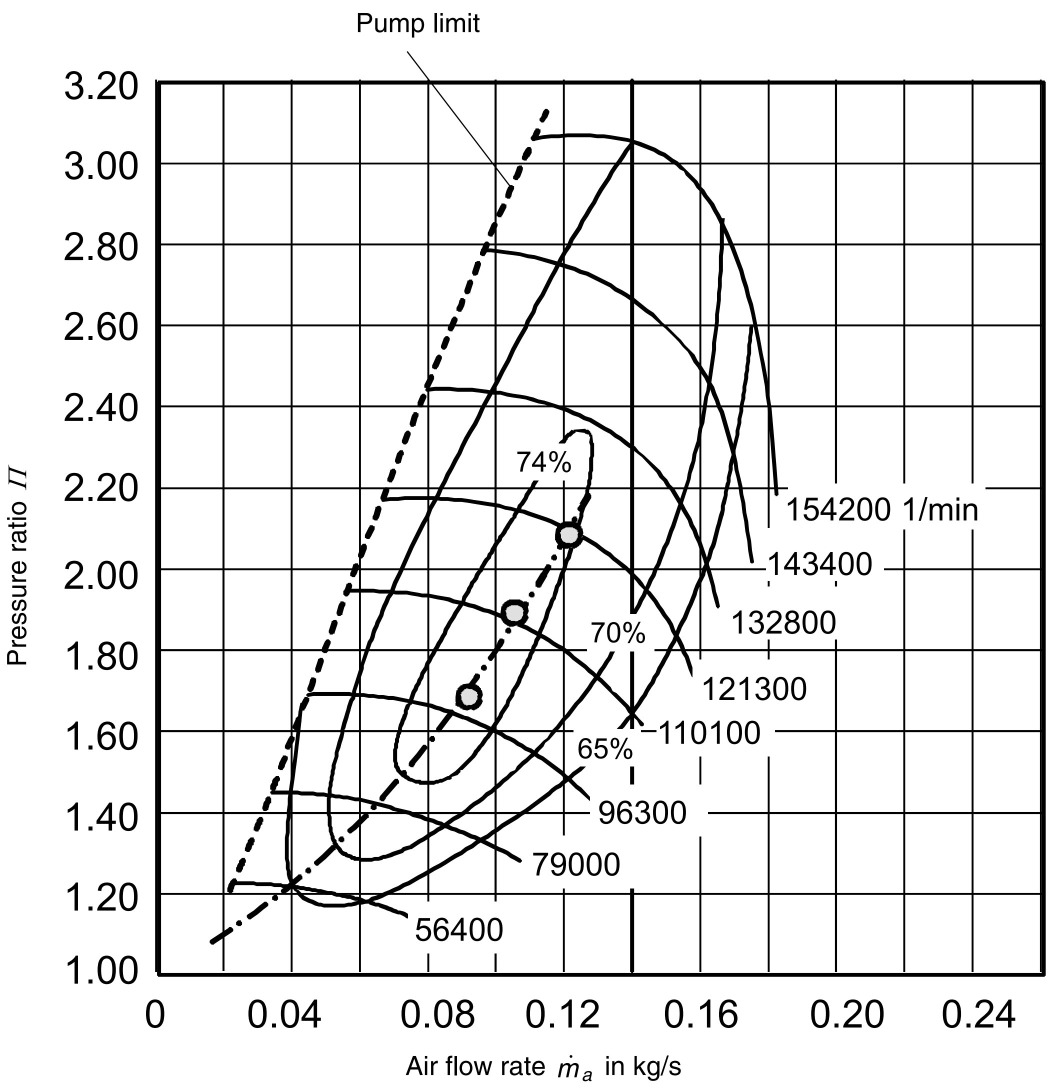


Fig. 5.2 Compressor Map with Operating Points

5.3 Determination of compressor power

The power transmitted to the gas by the compressor is determined by the specific enthalpy values calculated by the software.

$$P_t = \dot{m} \cdot (h_2 - h_1) \qquad (5.6)$$

$$\dot{m} = \dot{m}_a = 0{,}106 \frac{kg}{s}$$

$$h_1 = 28 \frac{kJ}{kg}$$

$$h_2 = 94 \frac{kJ}{kg}$$

$$P_t = 0{,}106 \frac{kg}{s} \cdot (94 - 28) \frac{kJ}{kg} = 6.996 W$$

The power to be exerted by the gas in the gas turbine to operate the compressor is determined in the same way.

$$P_{GT} = \dot{m} \cdot (h_4 - h_3) \qquad (5.7)$$

$$\dot{m} = \dot{m}_a + \dot{m}_G = (0{,}106 + 0{,}0015) \frac{kg}{s}$$

$$\dot{m} = 0{,}1075 \frac{kg}{s}$$

$$h_3 = 972 \frac{kJ}{kg}$$

h_4 cannot be directly applied. The measured temperature value for calculation of h_4 is too low. This is caused by the distance of the measuring point from the turbine outlet and the heat radiation emitted from the pipe walls. These errors are significant due to the high temperatures of the combustion gas. The software compensates for these measuring errors by introducing an enthalpy h_{4_2}, shown as an additional point in the diagrams.

$$h_{4\_2} = 885\,\frac{\text{kJ}}{\text{kg}}$$

$$P_{GT} = 0{,}1075\frac{\text{kg}}{\text{s}} \cdot (885 - 972)\frac{\text{kJ}}{\text{kg}} = -9.353\,\text{W}$$

The negative sign is because this power is extracted from the gas.

Dividing the benefit P_t by the work P_{GT} gives the efficiency of the turbo compressor.

$$\eta_{TV} = \frac{P_t}{|P_{GT}|} = \frac{6.996}{9.353} = 0{,}75$$

5.4 Isentropic compressor efficiency

The isentropic efficiency of the compressor takes into account all fluid mechanics losses.

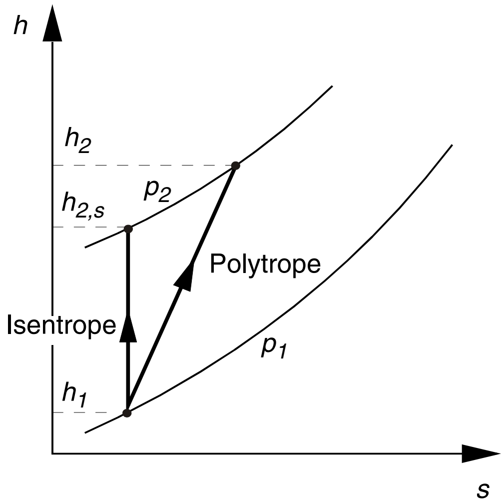


Fig. 5.3

$$\eta_{i,s,v} = \frac{h_{2,s} - h_1}{h_2 - h_1} \quad (5.8)$$

$$h_1 = 28 \frac{kJ}{kg}$$

$$h_2 = 94 \frac{kJ}{kg}$$

$h_{2,s}$ can be determined from the h,s diagram. As shown in Fig. 5.3, this is done by plotting the isentrope from h_1 to the isobar p_2 and reading off the enthalpy $h_{2,s}$ at the intersection of the isentropes and isobars.

$$h_{2,s} = 79 \frac{kJ}{kg}$$

$$\eta_{i,s,v} = \frac{79 - 28}{94 - 28} = 0{,}77$$

Because of their minimal effects, the dynamic components are ignored in this analysis.

5.5 Determination of the Power Turbine Output Power

To calculate the effective power output of the power turbine from the electrical power output, the efficiency of the generator and the belt drive must be taken into account. This is $\eta_{el} = 74\%$.

For full load it is found:

$$P_{Te} = \frac{P_{el}}{\eta_{el}} = \frac{1.683}{0,74} = 2.247\,W \qquad (5.9)$$

In addition, the measured output power must be reduced to sea level and 15°C in accordance with ISA.

$$P_{Tred} = \sqrt{\frac{T_1 + 273}{288}} \cdot \frac{1,013}{p_1} \cdot P_{Te} \qquad (5.10)$$

with $T_1 = 27,6\,°C$ and p1 = 1,020 bar, the reduced output power in accordance with ISA is

$$P_{Tred} = 2.307\,W \qquad (5.11)$$

For the thrust the calculations are the same:

$$S_{red} = \sqrt{\frac{T_1 + 273}{288}} \cdot \frac{1,013}{p_1} \cdot S \qquad (5.12)$$

with $T_1 = 9\,°C$ and p1 = 1,020 bar, the reduced output thrust in accordance with ISA is

$$S_{red} = 34,4\,N$$

5.6 Determination of thermal efficiency

As described in Chapter 4.1.1.1, Page 47, the thermal efficiency is determined as follows:

$$\eta_{th} = 1 - \frac{1}{\Pi^{0,285}} \tag{5.13}$$

With the compressor ratio:

$$\Pi = \frac{p_2}{p_1} = \frac{1,743}{1,013} = 1,72 \tag{5.14}$$

$$\eta_{th} = 1 - \frac{1}{1,72^{0,285}} = 0,14 \tag{5.15}$$

5.7 Determination of the Power Efficiency

The power efficiency of the turbine is calculated from the specific fuel consumption and lower calorific value h_u of the fuel. For propane the following applies:

$$h_u = 46.369\,\mathrm{kJ}/\mathrm{kg} \tag{5.16}$$

This yields for the power efficiency

$$\eta_e = \frac{3.600}{b_e \cdot h_l} = 0{,}0332 \tag{5.17}$$

For the above stated reasons, and the related low thermodynamic efficiency, the power efficiency of 3,3% is also very low. Referred to the electrical power generated, the efficiency is 2,4%.

It is to be noted that the efficiency of a two-shaft system increases continuously with effective power. The absolute fuel consumption $\dot{m}_G$ is independent of the output power of the power turbine at constant gas generator speed.

5.8 Determination of the Specific Fuel Consumption

The specific fuel consumption is calculated from the amount of fuel supplied and the useful power output. Here a differentiation is made between shaft power turbine with P_{Tred} and jet engine with S_{red}. For the shaft power turbine the following applies:

$$b_e = \frac{\dot{m}_G \cdot 3{,}6}{P_{Tred}} = \frac{1{,}50 \cdot 3{,}6}{2307} = 2{,}34 \frac{kg}{kWh}$$

Compared to other thermal prime movers, the specific fuel consumption is very high. The reason for this is the very low pressure ratio of 1,69 and the relatively low turbine inlet temperatures of 899°C. In addition, the small dimension of the system reduce the efficiency. For geometrically small dimensions, the tip clearance losses increase disproportionately. Also unfavourable surface / volume ratios increase radiation losses.

For the jet engine, the specific fuel consumption referred to the thrust is:

$$b_s = \frac{\dot{m}_G \cdot 3{,}6}{S_{red}} = \frac{1{,}75 \cdot 3{,}6}{34{,}4} = 0{,}183 \frac{kg}{kWh}$$

This is a very high value compared with large systems.

5.9 Determination of the Air Ratio

The air ratio is given by the quotient of the actual amount of air drawn in and the amount of air necessary for the stoichiometric combustion of the fuel.

The amount of air necessary to burn propane is:

$$a_{min} = 15{,}23 \cdot \frac{\mathrm{kg_a}}{\mathrm{kg_G}} \tag{5.18}$$

From which the air ratio at full load is

$$\lambda = \frac{1}{a_{min}} \cdot \frac{\dot{m}_a}{\dot{m}_G} = 4{,}64 \tag{5.19}$$

This quite high value for the air ratio corresponds well with the low turbine inlet temperature T_3.

6 Appendix

6.1 Technical Data

Dimensions

Length x width x height	1.500 x 680 x 1.820	mm
Weight	approx. 325	kg

Connections

Power supply:	400V / 3ph / 50	Hz
Alternatives optional, see type plate		
Water supply:	200	ltr/h
Fuel supply:		
Hose and bottle connection threaded fitting in accordance with DIN 4815/T2		
Fuel:	Propane C_3H_8	
Fuel pressure:	3...15	bar
Exhaust fitting pipe:	Ø 89	mm

Noise exposure

Sound level at 1 m distance:	80	dB(A)
(Operation as jet engine):	110	dB(A))

Type of design

- 2-shaft turbine consisting of gas generator and freely rotating power turbine, open process.
- Operation as jet engine possible by uncoupling the power turbine and fitting a thrust nozzle.

Gas generator

Type of design: Radial compressor and turbine

Single Combustion Chamber with Parallel Flow

Speed range:	60.000...125.000	rpm
max. pressure ratio:	2,2	
max. fuel consumption:	120	g/min

NOTICE

Device-specific information on the continuous power and peak power are in the acceptance report to the cabinet door, left side, below..

- The continuous power is generally 1,5 kW
- The peak power is generally 1,99 kW
- The peak power can only be requested for maximum 10 min.

Power turbine

Type of design:	Radial turbine	
Speed range:	10.000...35.000	rpm
Continuous speed range with full load:	15.000...30.000	rpm
Output power, mechanical:	0...2,0	kW
Output power, electrical:	0...1,5	kW
Max. continuous power according to DIN6271A		
(can be overloaded by 20% for 0,5 h/12 h)	1,25	kW
Asynchronous generator with frequency converter	2,2	kW
Generator efficiency:	approx. 74	%
Braking resistors:	4 x 600	W

Ignition system

High voltage long duration sparks with ignition plug

Ignition voltage:	> 10	kV
Ignition plug type:	BOSCH F8LCR BERU 14F-8LUR Z4	

Starting system

Electrical operated starting fan

Rating:	1.000	W
Speed:	max. 16.000	rpm
Pressure:	max. 23,5	kPa

Lubricating system

Oil capacity:	4,5	ltr
Oil pressure:	2,0...3,0	bar
Oil quality:	SAE 5-W40 API/SE	
Oil filter:	BOSCH 0986452928	
Oil pump:		
Pump capacity:	4,5	ltr/min
Drive rating:	0,55	kW
Oil change interval:	200	h

Safety equipment

Fuel rapid action stop valve operated by:

Turbine inlet over temperature	$T_3 > 1.000$	°C
Combustion chamber flame out	$T_3 < 500$	°C
Lubricating oil over temperature	$T_{oil} > 100$	°C
No lubricating oil pressure	$p_{oil} < 1,5$	bar
Turbine gas generator	$n_1 > 125.000$	rpm

Lubricating oil run on after stop

Combustion chamber ventilation prior to ignition

Fuel only on ignition

Controls

- Master Switch
- Emergency Stop Switch
- Starting Fan Switch
- Rapid Stop Switch
- Ignition Switch
- Main Gas Valve
- Gas Valve Change-Over Damper
- Gas Pressure Regulator
- Gas Regulator Valve
- Power Turbine Loading Potentiometer

Instrumentation

Thermocouples and digital displays for the measurement of the following temperatures:

Type K	0...200 °C, ±3,4 °C
Compressor inlet T_1	
Combustion chamber inlet T_2	
Combustion gas prior the nozzle T_G	
Lubricating oil	
Type K	0...1.200 °C, ±3,4 °C
Power turbine inlet T_4	
Power turbine outlet T_5	
Type N	-0...1.200 °C, ±2,1 °C
Turbine gas generator inlet T_3	

Pressure sensors and digital displays for the measurement of the following pressures:

Gas supply	0...25 bar
Gas nozzle pressure	0...4 bar
Combustion chamber pressure loss	0...100 mbar
Turbine gas generator inlet	0...2,5 bar
Power turbine inlet	0...300 mbar

Mass flow rates

Air inlet measuring nozzle with square root law pressure sensor and digital display	0...100 ltr/s
Gas variable-area flowmeter	1,5...10,5 kg/h

Digital Tachometer

Gas generator	0...150 x 1.000 min^{-1}
Power turbine	0...50 x 1.000 min^{-1}

Digital display of generator electrical output power 0...1.999 W

Indicator lamps
- Lubrication oil pressure
- Starting fan
- Rapid action stop valve
- Ignition

Data acquisition

USB communication

Program environment: LAB-VIEW Runtime

Minimal system requirements:

Processor:	Pentium IV, 1 GHz
Disk space random access memory:	Minimum 1024 MB
Disk space on hard disk:	Minimum 1 GB
Interface:	1 x USB port
Graphics card resolution:	min. 1024 x 768 pixels, True Colour
System software:	Windows XP / Vista

6.2 List of the Most Important Symbols of Formulae and Units

Symbols of formulae	Mathematical / physical quantity	Unit
a_{min}	Amount of air	$\frac{\text{kg a}}{\text{kg G}}$
b_e	Fuel consumption, specific, elektric	$\frac{\text{kg}}{\text{kWh}}$
b_s	Fuel consumption, specific, thrust	$\frac{\text{kg}}{\text{kWh}}$
h	Enthalpy, specific	$\frac{\text{kJ}}{\text{kg}}$
h_u	Lower calorific value	$\frac{\text{kJ}}{\text{kg}}$
$\dot{m}_a$	Air mass flow	$\frac{\text{kg}}{\text{s}}$
$\dot{m}_G$	Gas mass flow	$\frac{\text{g}}{\text{s}}$
$\dot{m}$	Total mass flow	$\frac{\text{kg}}{\text{s}}$
n	Speed	min^{-1}
p	Pressure	bar
p_0	Pressure, ambient	bar
p_G	Pressure, gas	bar
p_D	Pressure, at the nozzle	bar
P_{GT}	Pressure, gas turbine	W
P_N	Power	W
P_t	Power, compressor	W
P_{Te}	Power, power turbine	W
P_{Tred}	Power, reduced, power turbine	W
q_{in}	Heat input	W

Symbols of formulae	Mathematical / physical quantity	Unit
q_{out}	Heat output	W
s	Entropy, specific	$\frac{kJ}{kg}$
S	Thrust	N
S_{red}	Thrust, reduced	N
T	Temperature	°C
T_0	Temperature, ambient	°C
T_G	Temperature, gas	°C
w	Compressor work	$\frac{kJ}{kg}$
w_N	Capacity to perform work, specific	$\frac{kJ}{kg}$
W	Energy, mechanical	W
κ	Adiabatic exponent	1
λ	Air ratio	1
η_e	Efficiency, power	1
η_{el}	Efficiency, electrical	1
$\eta_{\mathrm{i,\,s,\,v}}$	Efficiency, isentropic, compressor	1
$\eta_{\mathrm{i,\,s,}\,NT}$	Efficiency, isentropic, power turbine	1
η_{th}	Efficiency, thermal	1
η_{TV}	Efficiency, turbo compressor	1
Π	Pressure ratio	1
ρ_0	Density, specific, air	$\frac{kg}{m^3}$

6.3 Working Sheet Recording Measured Values

Experiment gas turbine Ambient temperature in °C: Air pressure in bar: Relative humidity in %:	Date:					
Experiment No.:	1	2	3	4	5	6
Gas T_G in °C						
Gas nozzle p_D in bar relative						
Compressor inlet T_1 in °C						
Compressor outlet T_2 in °C						
Combustion chamber pressure loss p_2-p_3 in mbar						
Turbine inlet T_3 in °C						
Turbine inlet p_3 in bar relative						
Turbine inlet p_3 in bar						
Power turbine inlet T_4 in °C						
Power turbine inlet p_4 in mbar relative						
Power turbine inlet p_4 in bar						
Power turbine outlet T_5 in °C						
Air flow rate in ltr/s						
Air flow rate $\dot{m}_a$ in kg/s						
Gas flow rate in kg/h (2 bar; 0 °C)						
Gas flow rate $\dot{m}_G$ in g/s						
Speed n_1 in 1/min						
Speed n_2 in 1/min						
Electrical power P_{el} in W						
Thrust S in N						
Oil temperature T_{oil} in °C						
Comment						

6.4 Compressor Map

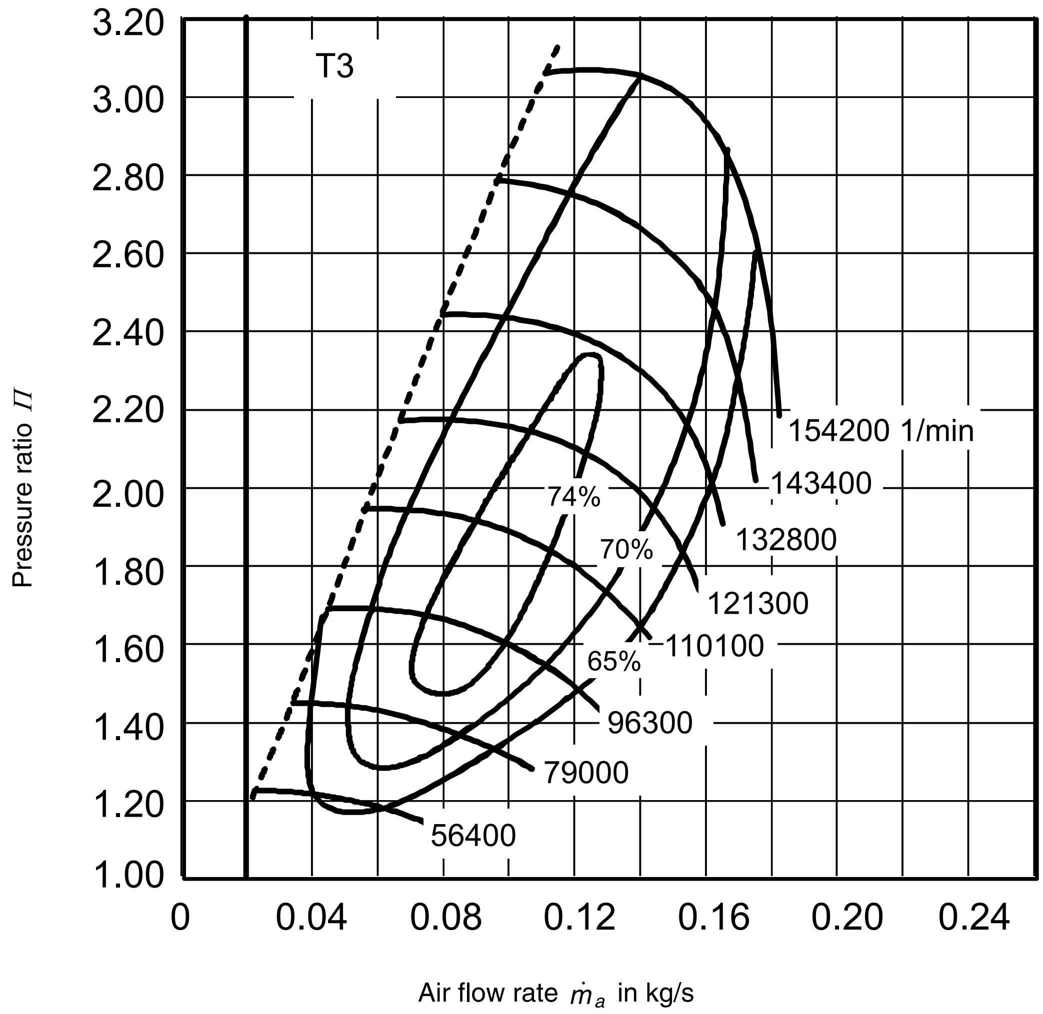


Fig. 6.1

6.5 Index

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