Small Gas Turbines by Ian F Bennett

Chapter 8

A Home Constructed Gas Turbine Engine

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Constructing any kind of gas turbine engine which resembles that which is fitted to an aircraft, or an industrial unit would be an enormous task. Gas turbine engines consist of many component parts that are manufactured to the highest standards and closest tolerances, also the materials that are used are expensive, difficult to obtain and awkward to work with. The rotating components of gas turbine engines also must be dynamically balanced to within close limits.

It is possible to construct a gas turbine engine for the propulsion of model aircraft, these units are simpler to build than commercial engines but still require a high level of skill and facilities. Dynamic balancing of the rotating system is also required. Model gas turbines require servicing of the bearing systems after only a few hours of operation. It is however possible to construct a working gas turbine engine from an automotive turbo-charger unit utilizing relatively modest engineering skills.

A gas turbine engine may be built from a complete automotive turbo-charger unit, in this case the precision fabrication and balancing has already taken place, a basic gas turbine engine may be simply created by adding a combustion chamber between the turbo-charger compressor outlet and the exhaust turbine inlet. Automotive turbochargers are robust and their heavy cast-construction helps reduce the risks associated with the high speed rotational core. A correctly lubricated unit will have a life expectancy that is almost indefinite when compared to a model turbo-jet engine. Turbo-based engine runs very well, it cannot be considered a viable propulsion engine (Although many have demonstrated moderate but viable thrust to weight ratios) or indeed a shaft drive unit. The engine is too heavy for many propulsion applications and adding a reduction gearbox and shaft drive would be very complicated. The turbocharger-based gas turbine does however demonstrate all the characteristics of a running gas turbine engine and may form the basis of a test bed or may simply provide fun and amusement.

The author’s turbocharger-based gas turbine engine first ran in a very crude form, over a period of time, the design was improved and modified until an acceptable demonstration unit was realized.

In addition to the turbocharger itself the following systems are required to produce a viable running engine-

1. Combustion System – simple home or workshop fabricated can type unit.
2. Fuel System – A simple propane gas supplied burner nozzle.
3. Lubrication – Pressurized circulating oil system driven by a pump.
4. Ignition System – A simple spark plug and coil or more complex electronic exciter.
5. Starting System – High-pressure air impingement starting or windmill starting by the application of a forced air blower at the compressor inlet.
6. A choice of Instrumentation may be provided depending on the intended purpose of the engine.

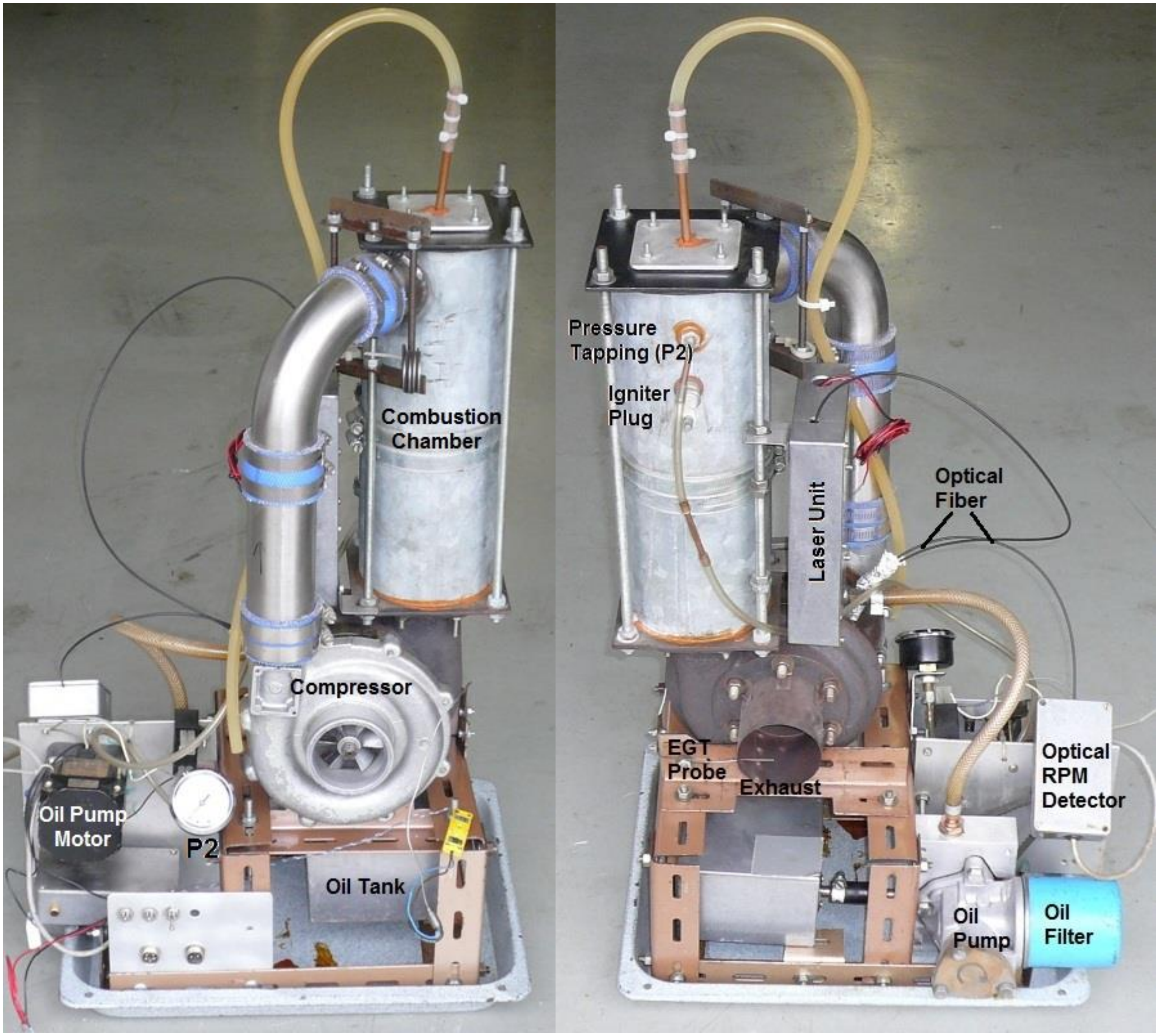
Basic Turbocharger unit

The gas turbine is built around a automotive diesel turbo-charger, the type used is a Holset 3LD unit and was obtained scrap from a diesel truck. The turbo consists of a three-inch aluminum compressor wheel which is coupled to a radial inflow turbine wheel. The rotor of the turbo is dynamically balanced to prevent vibration and resonances. The turbo is of entirely conventional construction, the turbine is incased in a cast iron volute that incorporates a nozzle. The nozzle itself differs from gas turbine practice and may almost be considered a vane-less nozzle. It may also be considered to be two nozzles that lie side by side along the axis of the turbine. The exhaust gas inlet to the turbine splits into two at the connecting flange, two chambers are formed in the volute which then discharge onto the turbine wheel around its circumference. The exhaust gases passing through the turbine and are ducted out along the turbine axis where a connecting flange is provided to accept an exhaust pipe.

The compressor section employs a vane-less diffuser (No stator blades), this consists of a divergent aperture surrounding the compressor wheel circumference and a scroll type air collector. The compressor casing forms the air scroll and a discharge port, this casing is made from cast aluminum.

The bearing system is placed between the compressor and turbine wheels. A plain journal bearing is employed, it consists of an outer cast iron casing which is bored at the centre, a phosphor bronze bush runs in the bearing bore and a steel connecting shaft for the compressor and turbine runs in the bush. A thrust face is provided at the compressor end of the shaft to prevent significant axial movement. The bearing is pressure lubricated by a feed through the casing via a drilling, a cavity in the casing collects the oil once it has passed around the bearing journal it then drains under gravity out through a pipe at the bottom. The bearing casing forms the centre of the turbo, the exhaust volute is clamped on to it at the turbine end, and the compressor scroll is bolted to it at the compressor end.

The clearances are such that under no oil pressure some radial movement and axial movement of the rotor is possible. During operation the oil pressure holds the rotor in place and a film of oil is formed on the bearing surfaces, the oil also dampens any vibration as the rotor speed varies.


Combustion Chamber
Compressor
Oil Pump Motor
P2
Oil Tank
Pressure Tapping (P2)
Igniter Plug
Laser Unit
Optical Fiber
EGT Probe
Exhaust
Optical RPM Detector
Oil Pump
Oil Filter

Combustion chamber

It terms of the gas turbine working cycle definition, the addition of a combustion chamber to the turbo based engine completes it. The combustion chamber is fabricated and then inserted between the compressor outlet and the turbine inlet.

The picture below illustrates the combustion chamber design. The outer casing is constructed from a 3mm steel cylinder that is enclosed at each end by two plates. The combustion chamber is oriented vertically that eases assembly. The bottom combustion chamber end plate is bolted to the turbo exhaust volute input flange, a hole which matches the volute inlet aperture is cut into the plate to allow the combustion products to pass into the volute.

The cylindrical outer casing is fitted with a 2 1/4 inch air inlet pipe, a short length of stainless tube is welded into the top of the cylinder. Two more holes are placed in the cylinder, one provides a mounting for an igniter plug, the other allows a P2 air bleed for instrumentation.

The combustion chamber top plate is drilled at the centre to provide access for a gas burner ring supply tube. The tope and bottom plates are square, at the corners four threaded bars clamp the plates together with the combustion chamber outer casing sandwiched between them. At the bottom plate, the casing is sealed onto the plate by using automotive exhaust paste. At the top plate, sealing is achieved by using a rubber gasket.

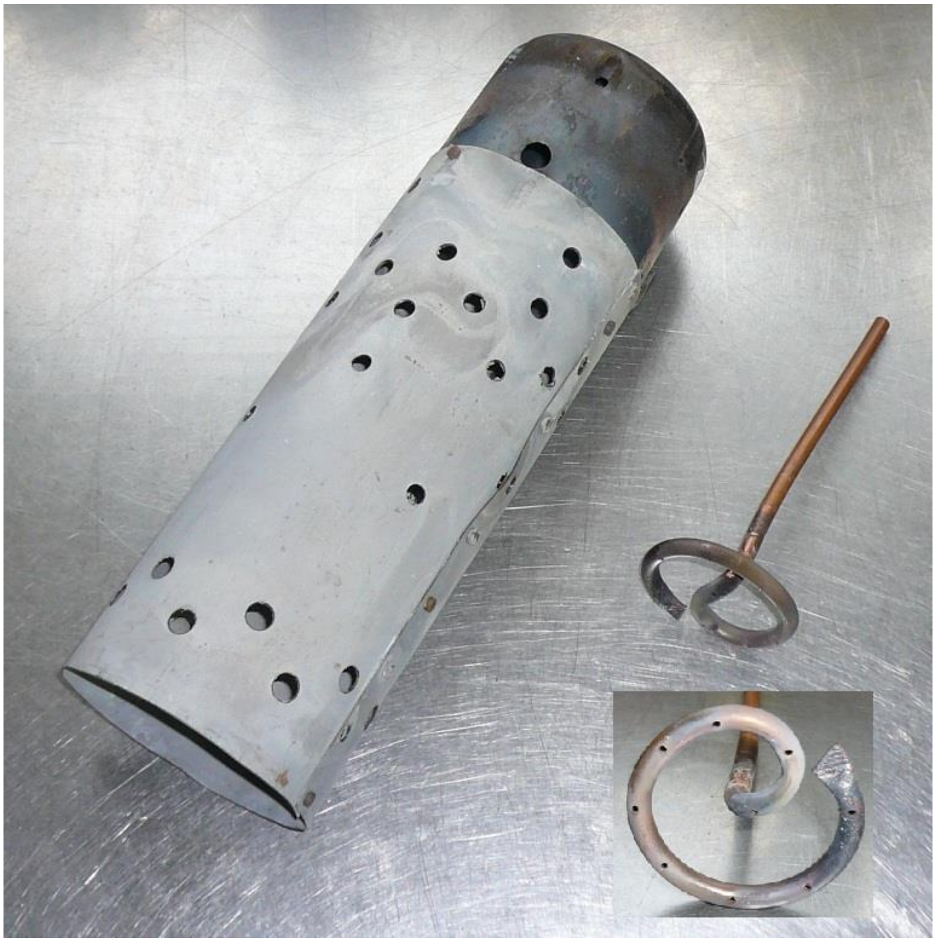
Inside the combustion chamber casing a cylindrical metal liner has been placed, this acts as a "Flame Holder" for the combustion process. The liner is made from 0.5mm steel sheet, ideally this should be stainless steel (For corrosion and higher temperature resistance), stainless is more difficult to drill and cut than mild steel, mild steel will suffice if facilities to work with stainless steel are unavailable. The liner is open at the bottom end and is placed over the turbine inlet. The top of the liner must be closed off, to do this a domed cap is placed upon it. The cap makes use of a redundant gas cartridge, the steel cartridge is formed in the right shape for the cold primary end of the liner. The cap is fastened to the liner cylinder by three small M 2.5 stainless steel screws.

It was originally intended that different liners with various air distributions would be investigated. The liner described was only the second to be used, the thermodynamic results were found to be more than satisfactory considering the minimum of theoretical design effort that went into its design. One orifice near the top provides a location for the igniter plug, the plug protrudes into the combustion zone where it ignites the flammable gas omitted by the burner ring.

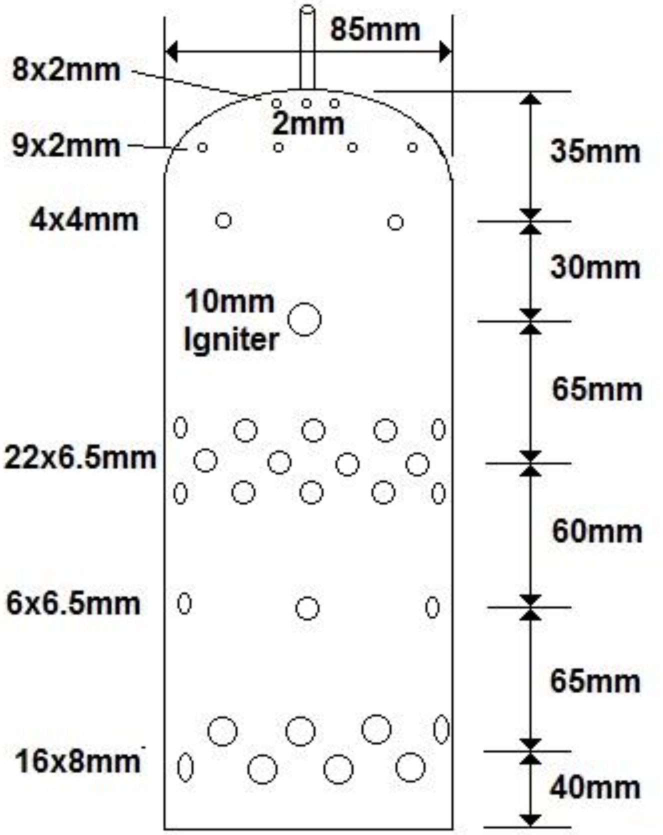
The overall holes spacing (see diagram) and positions are not critical, this type of simple engine is tolerant of differing air distribution within the combustion chamber as the overall volume is generously dimensioned for the available air mass flow.

A burner ring is placed inside the domed end of the combustion chamber liner. The ring is formed from a length of 1/4 " tube, the tube is bent around into a circle, one end is crimped the other is brought out at the geometric centre of the ring. The ring is drilled with 10 1mm holes, these holes admit the propane gas fuel into the combustion zone. The ring is supported by its central fed tube, the tube passes through the top of the combustion chamber dome and is retained by a small clamp, finally the tube passes out of the combustion chamber through the top plate. A seal at this point is unnecessary, the hole around the fed tube is made a snug but running fit around the burner supply tube. Very large quantities of air flow through the engine during operation, any small leaks are insignificant and do not have a serious effect on efficiency.

The combustion chamber is aligned with the casing by means of the igniter plug and two brackets, these help maintain a gap between the liner and the outer casing. Compressor air flows between the casing and the liner before entering the combustion zone, this air keeps the outside surface of the combustion chamber casing cool. The liner is located at the centre of the casing at the bottom by four bolt heads, the bolts also secure the combustion chamber bottom plate to the turbine inlet volute.



Combustion chamber liner/flame tube with burner ring (inset)



Combustor liner layout

Compressor delivery tube

Air from the compressor is ducted to the combustion chamber by a tube. The compressor outlet is connected to a 2" diameter stainless tube by means of short connecting hose. The hose is designed to be used for turbocharger plumbing; it is secured with two pipe clips. The tube connects to a second right-angle stainless-steel tube that guides the compressor air into the combustion chamber casing. Again, the tube is secured at both ends by short lengths of hose and pipe clips. All full speed (About 100,000 rpm) the compressor will deliver about a 1 Bar of pressure (15 PSI), this places stress on the compressor tube and so all fittings must be secure.

If stainless steel tube is not available for this purpose it may be possible to use a plastic pipe to deliver air to the combustion chamber. A right-angle arched bend was originally fabricated for this purpose by gluing pipe segments together. Each segment was cut at an angle so that a total of five pieces formed a 90-degree bend. If plastic pipe is used care should be exercised, the pressure of the air delivery may cause it to fail, the engine may however operate satisfactorily at low "Boost" e.g. 1/4 bar (4 PSI).

Fuel system

The fuel chosen is propane gas. Using gas greatly simplifies the design of the burner system and also no fuel pump is required. The gas is supplied to the burner directly from a propane gas bottle, the shut of valve on the bottle is used as the throttle control and fuel shut off. The flow required from the bottle is very high, no regulator is used, and the bottle may require gentle heating to aid in the evaporation of the propane gas. A 3.9 Kg capacity bottle will last for about 20 minutes, this is due to the inherent high fuel consumption of the gas turbine.

Lubrication system

To operate satisfactorily the turbo charger requires a lubricating oil supply. When attached to a normal reciprocating engine the turbo would have received pressurized oil from the engine system, here, we must reproduce a similar system.

Oil is supplied to the turbo from a modified automotive oil pump. A ford unit is used which also incorporates an oil filter. This type originates from a ford cross flow OHV (Overhead Valve) engine, the pump is useful as it is an externally mounted unit instead of the more common sump mounted design. The pump body is designed to bolt onto the engine cylinder block, the oil suction, oil delivery and the pump drive are received through a mounting face. For the gas turbine application, a connection block is fabricated which the pump is bolted on to. The block provides galleries that duct oil to and from the pump via hose fittings. The pump drive shaft also passes through the block where it is fitted with an oil seal.

Belt-driven oil pump with mounting block and motor

A diagram shows how the pump mounting is constructed. The oil pump is supplied with a drive pinion attached, the pinion should be removed by extracting a roll pin from it and using a puller to extract the pinion gear from the shaft. The shaft will then push through the oil seal as the pump is fitted to the body, once in place the pump shaft is fitted with a drive pulley.

The oil pump is driven by a small electric motor. A toothed belt reduction drive reduces the motor speed and increases the torque. The torque required to turn the pump varies according to the temperature of the oil, when cold the pump is much harder to turn then when hot. The pump reduction is about 5:1 yielding a speed of about 300 rpm, this provided circulation roughly equivalent to the piston engine idle speed, lubrication of the turbo will be adequate at this speed.

An alternative to the automotive pump is to use a purpose-built motor driven oil pump or hydraulic gear pump driven by a motor. Pressure relief valves should be fitted to maintain moderate pressure to the turbo. Some experimentation may be required to establish the optimum oil pressure feed setting. Values between 20-100 PSI should be satisfactory, when cold some starting difficulties may be experienced so the ability to vary the oil pressure and reduce it during starting will be beneficial.

An oil reservoir is placed underneath the main turbo-charger body. Oil from the reservoir is drawn into the pump where it is filtered and pressurized, the oil then feeds the turbo bearing assembly via a short hose. The oil returns from the turbo through a 1/2" pipe under the force of gravity into the reservoir.

The oil reservoir is fabricated from a pre-formed aluminum box. Two holes are provided in the lid, one for the oil drain/return the other allows for filling and inspection of the oil. The oil temperature may be monitored by inserting a thermocouple probe into this hole.

The oil specification used for the turbo is a conventional automotive grade. Synthetic oil is used as this type is often recommended (although not essential) for automotive turbo charger installations. About a 2 litre quantity Mobile 1 formula is placed in the oil reservoir. The pump was found to run fast for a few seconds until the oil was drawn into it and then circulated into the turbo. Turbine oil should not be used for this purpose, the turbo is designed to be lubricated with automotive oil, turbine oils are lower viscosity and are designed for ball race type bearings and not plain bearings.

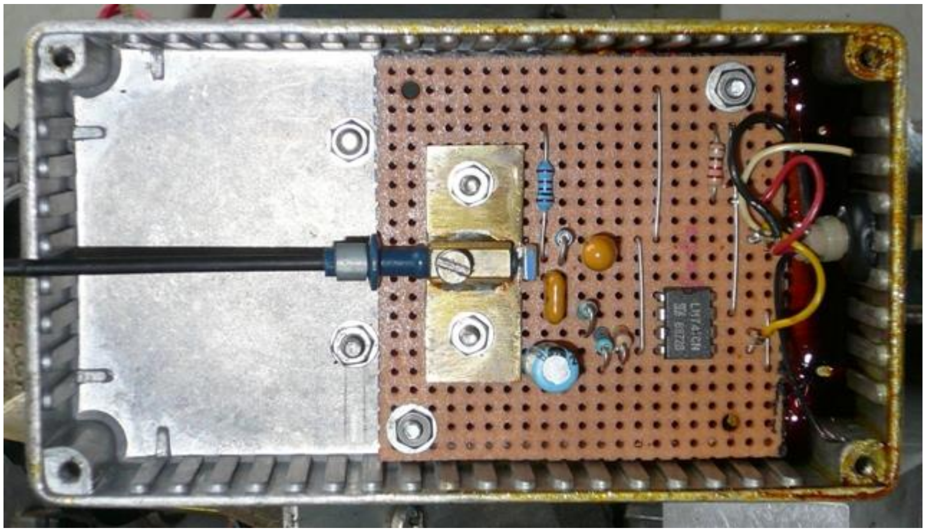
Instrumentation

As with any other gas turbine engine, the two most important parameters are speed and temperature. For experimental engine designs compressor delivery pressure (P2) is also a useful quantity to measure.

An optical method was chosen to detect the rotation of the compressor. The rear face of the compressor is half painted with matt black paint, the other half is polished to a mirror finish. A small hole is drilled through the compressor casing rear face, two polymer optical fibres are passed through the drilling and terminate close to the painted edge of the compressor wheel. A visible red laser tube illuminates the far end of one of the fibres, this intern illuminates the back face of the compressor. The second optical fibre picks up reflected light from the compressor wheel and caries it to an electronic detector. As the compressor rotates, the reflected light from it pulses on and off once every revolution, this generates an optical signal which is processed to produce a RPM indication.

The laser ensures optimum illumination of the fibre, the fibre system was found to be inefficient so plenty of illumination was required. Using incandescent lamps to illuminate the fibre caused too much heat to be developed and coupled into the fibre inefficiently.

The detector consists of a photo diode unit with an integral amplifier. The detector produces a string of pulses that are further amplified by an operational amplifier. The detected pulses are then counted by a charge pump frequency to voltage converter I.C. (Integrated Circuit) type LM2907. The LM 2907 will drive a 0-10V moving iron meter that has been calibrated 0-100,000 rpm. One pulse is produced per revolution of the compressor, when turning at 60,000 rpm the engine produces a signal of 1 KHz in frequency.



Optical fiber receiver and amplifier

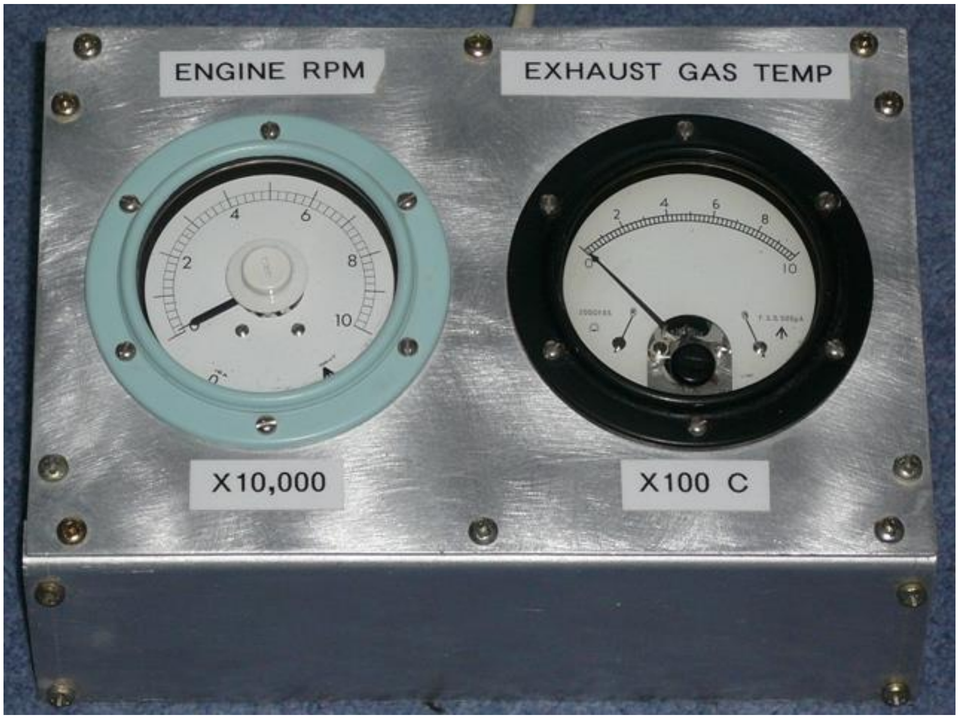
The speed sensing system is built around the back of the compressor, this allows the front air intake area to be kept free from sensors and pickups. The uncluttered front of the engine allows for easier coupling of the starting air blower.

When operating the engine, the signal from the tachometer system should be monitored at different engine speeds to ensure that it is operating correctly. Failing or false indications at speed could be dangerously misleading. It is always important with any speed measuring system to ensue that it is calibrated and functioning correctly.

Exhaust temperature is measured using a thermocouple amplifier I.C. An AD595 amplifies the signal provided by a "K" type thermocouple, the thermocouple is placed in the exhaust outlet of the engine. An inconel 1mm diameter "K" type probe provides a fast response time to temperature changes and resists the high starting temperatures which are encountered with this engine.

The AD595 is supplied from a regulated DC supply, it coverts a thermocouple signal into a DC signal, 0-1000 degrees C produces a 0-10V signal. The exhaust gas temperature is displayed on a standard moving coil meter.

The compressor delivery pressure P2 is displayed on a normal pressure gauge. As the engine runs it was found that the pressure tapping was providing an unstable air supply. The gauge pointer was found to fluctuate quickly making the reading hard to judge. A restriction was placed in the fed pipe to the gauge, this dampens down the reading allowing for a sensible indication of P2.



Instrumentation RPM and EGT

Ignition System

Reliable ignition of the propane gas fuel has proved to be one of the more difficult tasks when constructing and testing the turbo-based gas turbine. The igniter itself is made from a conventional automotive spark plug. A motorcycle device is used, it has a particularly long reach which is required so that it is properly inserted into the combustion zone. A problem with many spark plugs when used in this application is that they contain a resistor. A resistor is placed inside the plug body which helps suppress radio interference, interference is not a major problem in this application as the igniter will be switched off when the engine has been started. The resistor has the effect of reducing the ferocity of the spark as it dissipates energy in the body of the plug and not at the spark gap.

There are several ways of supplying sparks to the igniter plug. An electronic switching circuit was used which operates an automotive ignition coil, this provides a series of high voltage low energy sparks at a rate of about 50 per second. This system worked on occasions, but it was found that the combination of fuel and air required for satisfactory ignition was quite critical.

A more reliable system made use of an aircraft igniter system, this provided a series of high frequency sparks from a trembler coil/capacitor system. This unit provided high voltage sparks but at higher energy than that of the automotive system. The system produced an almost continuous arc at the spark plug gap.

The above ignition systems made use of a local 24V battery supply, if available a mains system can be used. Neon sign transformers or industrial heating ignition transformers may be used to provide a spark. These transformers provide a very hot continuous arc that is ideal for ignition of the gas. The open circuit voltage of these devices may approach 10,000 V, great care must be exercised when using them as they can provide a lethal electric shock. Always make sure that the transformer body is earthed to the engine metalwork and provide a warning light so that it can be seen when the ignition system is "Live".

Warning: ***All ignition systems are dangerous. Exercise extreme caution when working with high voltage ignition systems!***

Starting system

One of the keys to the success of the turbocharger based gas turbine is the provision of an effective starting system. There are two main methods for starting this type of engine, "air impingement starting" or "windmill starting." Air impingement starter consists of a jet of high-pressure air that is directed onto the compressor rotating inlet guide vanes. The impeller becomes a simple impulse turbine and is forced to rotate. A high-pressure compressed air cylinder is required for this operation, air at up to 2000 PSI is directed through a small nozzle which placed in the air intake region of the turbo. The system will rotate the engine for only a limited period before the air supply becomes exhausted, this may be inconvenient if the engine fails to light up quickly or is slow to accelerate due to oil drag.

A windmill starting system may also be used with the turbo charger, this was the system chosen and found to provide satisfactory results. A second turbo charger compressor unit is driven by an electric motor that forms a blower; this provides a flow of air which is coupled directly into the gas turbine air intake. The air-flow provided by the blower is sufficient to sustain combustion and rotate the engine. The initial speed of rotation is relatively slow (As low as 3,000 rpm) but as the combustion heats the oil, the engine rotates faster and eventually self sustains.

The blower is coupled directly to the engine air intake, as the engine starts and becomes self-sustaining the blower must be removed from the air intake so that the engine can ingest still air. The point at which the blower is pulled off must be judged carefully and may need some practice, too early a removal will cause the engine to stop. Late removal is less of a problem, the blower attachment becomes restrictive to the engine air flow and causes high exhaust temperatures.

The blower was fabricated from the compressor section of another identical Holset turbo. A rear plate is made up which supports the motor and is bolted onto the aluminum compressor air scroll. The motor used is a mains electricity powered universal type that spins at around 13,000 rpm when loaded by the blower. The blower motor is connected to a triac operated dimmer unit so that the motor speed can be varied, the dimmer is a conventional unit which acts as a power controller for the motor. The power control is useful, the blower output can be varied over a wide range, the blower is turned down during engine light up and then turned to full power for starting.

Motor driven blower unit used for starting

Starting and operating the engine

Starting a home-built gas is not quite a push button affair, a number of devices require sequenced operation and a certain amount of judgment is required. With practice an operator can gain a feel for how the engine operates and reliable operation should be possible. It may be advantageous to have an assistant to help with various tasks, all the usual gas turbine safety precautions should also be adhered to.

The basic principle behind starting the engine is to light it up first at low airflows, it should then be warmed up so that the oil becomes thinner and allows for a faster initial rotation. Once warmed up the engine is then accelerated by increasing the fuel flow until a point is reached where the starting air is removed, and the engine self sustains. During starting the oil supply is turned on and off to reduce the drag on the rotor, when the engine self sustains the oil supply is turn on permanently.

To start the engine it is firstly is supplied with air from the blower, the blower is turned down so that at this point only a breeze is present through the engine. At low settings and with a cold engine, the air flow is insufficient to rotate the engine, but enough is present to initiate combustion. The oil supply should also be turned on briefly and then turned off to supply a metered amount of oil to the turbo charger bearing. The ignition should now be switched on and the gas valve on the bottle slowly opened, a small amount of propane is required for ignition, too much gas results in a delayed light up which may be accompanied by a large bang. When compared to liquid fuel systems, propane seems more difficult to light, a more precise fuel/air ratio is required. Excessive air flows may also prevent satisfactory ignition, after a few seconds and the engine has not lit up, turn the gas of and run the blower at full speed to purge the combustion chamber of any residual gas.

When the gas turbine lights, a low-pitched rumble will be heard coming from the combustion chamber, the airflow and gas flow can be increased a little so that the engine can be warmed up. A cold engine rotates only slowly due to the increased drag from the cold oil, as the oil warms the rotor will begin to speed up. The fuel flow should be adjusted to produce an exhaust temperature of about 300 degrees, at this point the engine speed will be only a few thousand RPM. A period of about I minute should be allowed to heat up the engine. During the warmup phase periodically switch on the oil supply for a few seconds to ensure lubrication.

After it has been satisfactory warmed up the engine can be started. The air blower is turned up to full power and the gas flow increased, at this point the RPM should begin to rise. Gradually increase the gas flow and adjust it so that the rotor accelerates noticeably, when wearing ear defenders, the compressor whine should be heard to increase. If too much gas is supplied, the combustion will become over rich and inefficient, flames will appear in the exhaust and the engine may also become unnecessarily hot. The exhaust temperature and the RPM should be watched closely, the RPM should be built up by carefully increasing the gas flow, at about 30,000 rpm the compressor will begin to show a significant pressure rise and the engine will self-sustain. The blower should then be pulled off and the gas flow increased to quickly accelerate the engine to a sensible idle speed of about 50,000 rpm. At idle speed the oil supply can be switched on and left on so that the engine is continuously lubricated.

Failure of the engine to start may be due to several reasons-

If the oil is too cold the engine will not self sustain, a longer warming up period should be allowed.

Significant gas flow is required to run the engine, if this can't be obtained, the propane bottle should be gently heated by placing it in a bowl of warm water.

The blower described should start the engine, all the air from it should be directed through the engine to maximize the air flow. Other blowers such as garden leaf blowers may be suitable, small electric blowers or hair dryers are unlikely to provide enough air for this purpose.

Once running at a steady speed the exhaust temperature should drop to about 450 degrees C, this will depend on the efficiency of the combustion chamber, the compressor speed and the oil temperature. At high RPMs the drag on the rotor due to the oil supply is less significant as compared to that of the compressor load, in this case the oil temperature has little affect.

As the engine runs the exhaust temperature, RPM and P2 may be monitored. Increasing the propane gas fuel flow should accelerate the engine, during acceleration the exhaust temperature will rise, degreasing the fuel flow will decelerate the engine. During deceleration the exhaust temperature will fall until the engine settles at a slower speed, it will then rise slightly.

The maximum permissible speed and exhaust temperature depends on the condition of the turbo. If the unit runs very hot, the oil supply may be over heated as much heat is dissipated by the turbine casing close to which it passes. The maximum speed and pressure will depend on the fuel flow available; it is not advisable to operate the unit beyond 100,000 rpm.

The engine is shut down by simply cutting the propane gas supply, it will run down very quickly at first and then spool down at a slower rate. The oil supply should be switched off when the speed reduces to 10,000 rpm, if left on the sealing in the turbo may not be very effective and it will fill up with oil.

If the engine is to be restarted when hot, it will be found to be an easier operation, the hot rotor spools up more quickly.

Conclusion

The turbocharger based gas turbine makes an ideal demonstration unit, the main disadvantage is of course that it cannot be used to provide useful power, but it does enable the main features of a gas turbine to be investigated. The engine may be built at the fraction of the cost of a commercial APU, it is also cheaper and more robust than model propulsion units.

The gas turbine could be developed further, there are specific areas that warrant further attention-

1. The combustion chamber fabrication is crude, and it is also quite large, a more compact unit could be constructed with more efficient air distribution and better materials. Over time, the combustion chamber liner distorts due to the regular heat cycles. A certain amount of carbon was found to build up on the burner ring, this suggested that the air primary air distribution at this point could be improved.

2. The ignition system could also be improved. A high-energy system was tried which uses a special surface discharge plugs originally intended for racing IC engines. The high-energy system yielded more reliable and predictable light up. A development to the ignition system was the adoption of a high-energy capacitive discharge igniter system. The combination of an electronic exciter and surface discharge plug proved to be more effective at igniting the propane fuel. The plug used was a special automotive racing car device that consisted of a surface gap with no protrusions. The electronic exciter consisted of an inverter that is used to charge a 1uF capacitor up to around 2000V. The capacitor is connected to the igniter plug and an additional trigger circuit initiates a flashover across the plug gap. The trigger circuit provides a small high voltage spark which breaks down the air gap and provides an ionized path which the capacitor flash over current follows. Diodes were used to isolate the trigger voltage from the capacitor so that they can be combined in one connection to the plug. Electronic igniter systems may become quite complex in the areas of inverter and trigger technologies.

The position of the igniter plug within the combustion chamber could also be optimized.

3. After extended operation beyond about 10 minutes the oil temperature was found to be high. A permanently rated engine will benefit from an oil cooler system. When cold the oil flow could also be controlled electronically to maintain optimum lubrication without slowing the engine.

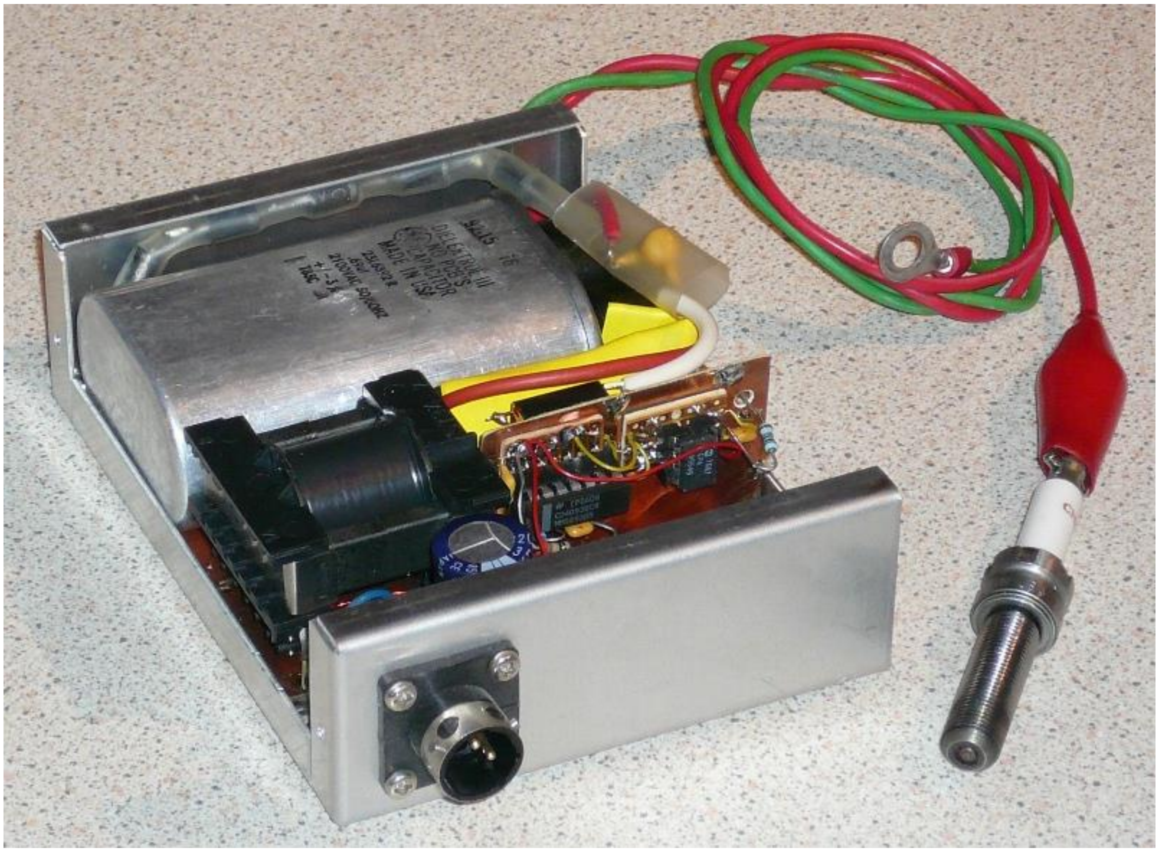
4. The RPM measurement system makes use of an elaborate laser system and optical fibres, this system could be replaced by a simpler magnetic pickup system or an optical system aimed at the front of the compressor.

5. In interesting experiment is to view the combustion process as it occurs, it is possible with a suitably placed window to the flames inside the combustion chamber. A window can be placed in the outer combustion chamber casing and the positioned in such a way so that the flame can be viewed through one or more air holes.

The engine described was fitted with an experimental window. The plate which forms the top of the combustion chamber was replaced with one made of Perspex material. A thick 10mm square of Perspex was constructed and bolted down with a rubber gasket and a hole in the centre allowed for the fuel delivery tube.

During engine operation, parts of the flame could be just seen through the air holes in the top part of the combustion chamber liner. The Perspex top plate is cooled by the incoming compressor air so little or no distortion of the plate was experienced.

Although the combustion process could be partially seen, the view is predominantly at the top of the combustion chamber, so the window did not allow for any significant inspection of the flame distribution along the length of the flame tube. A window on the side of the combustion chamber would be more difficult to engineer but would give a better view of the internal operation of the combustion chamber.



Advanced high energy discharge ignition exciter