Multi-Pressure Gas Turbines

Introduction

Gas turbines offer high reliability, low maintenance, few emissions, excellent torque curves, good fuel flexibility and little noise or vibration. Virtually every major automobile and truck manufacturer has built and tested gas turbine-driven vehicles. Yet only a few vehicular gas turbines have ever made it into production and those were for military applications.

Although large production could reduce the present high cost, three basic problems would still limit the acceptability of gas turbines for vehicles:

- High fuel consumption at full load.
- High fuel consumption at part load.
- Slow response time to throttle movement.

Yet each of these problems is solvable without using extraordinary technology. We know that recuperated intercooled cycles offer high efficiency at full load. This is a proven concept. The patented Agile Turbine Technology concept simulates operation at altitudes of 29,000 feet and 54,000 feet to allow close to 100% load fuel efficiency at 31% and 9.5% loads. In addition, the Agile gas turbine will be able to go between any of these power settings in less than fifty milliseconds with no thermal or mechanical shock.

Military vehicles could idle for extended period with low fuel consumption, and then jump to full power virtually instantaneously. Generator sets would offer excellent fuel efficiency at very low loads for silent watch. When a threat appeared, full power would be available within fifty milliseconds.

There are many applications for the Agile concept in the civilian world. Buses and trash trucks would have full power available for acceleration or hill climbing. So would delivery trucks, such as those of FedEx, UPS and the post office. Yet in the reduced power mode of cruising in traffic, fuel efficiency would still be excellent. When idling for traffic lights, passenger loading or deliveries, fuel consumption would be minimal. When high production economy of scale brings the cost down, SUVs and automobiles could become a prime market.

Increasing Full-Load Fuel Efficiency

Fuel efficiencies in the forty three percent range can be achieved using a recuperated intercooled cycle. The Ford Motor Company reduced this cycle to practice in the early 1960s. They drove the truck (shown in Figure 1) across the United States. A Ford model 705 gas turbine rated at 600 hp powered it. The peak efficiency for that engine was 37% - dramatically higher than what competing gas turbines and diesel engines offered then. With today’s improved materials, aerodynamics and recuperator designs, many gas turbine
manufacturers project efficiencies in the 40% to 43% range for this cycle without exceeding 1800°F.

Figure 1

Figure 2 shows the flow diagram of a conventional vehicular gas turbine. Air is compressed in a compressor with one or more stages. This air is then preheated in a recuperator before it is heated to turbine inlet temperature in a combustor. The air then expands through the gas producer turbine which drives the compressor, and then through the power turbine which drives the output shaft through a reduction gearbox. The hot air leaving the power turbine is then ducted through the recuperator to preheat the air going into the combustor. The turbine wheels may have more than one stage. The compressor, recuperator combustor and gas producer turbine make up the gas producer section. The power turbine and reduction gearbox form the power section.

Figure 2

The flow diagram of a recuperated intercooled cycle is shown in Figure 3. It has at least two stages of compressors and two stages of turbines in the gas producer section. An intercooler is placed between the two compressors to lower the temperature of the air going into the second stage compressor. A reheat
combustor is placed between the first and second turbine stages in the gas producer to raise the turbine inlet temperature of the second stage gas producer turbine and the power turbine.

![Diagram](image)

Figure 3

Lowering the inlet temperature of the second stage compressor lowers the amount of power consumed by that compressor. This increases the power available at the output shaft and the overall efficiency.

The reheat combustor raises the temperature of the second stage gas producer turbine wheel and the power turbine wheel. Thus more power is available at a cost of additional fuel. However, the power turbine discharge temperature is also raised, thus increasing the temperature of the exhaust gases going into the hot side of the recuperator. This raises the temperature of the air going into the primary combustor and compensates for much of the fuel consumed by the reheat combustor. The power is increased more than the fuel flow is increased. Therefore the efficiency is improved.

Note that the second stage compressor discharge temperature is decreased because the intercooler decreased the inlet temperature. Thus more heat would have to be added to this air to bring it up to turbine inlet temperature. Fortunately, the recuperator can perform most of this function.

Figure 4 shows a flow diagram of the Ford model 705 gas turbine that used this cycle, the primary difference being that the power turbine was placed between the two gas producer turbine wheels.
Figure 5 is a computer run showing a 43.6% efficient recuperated intercooled cycle using components with modern day, readily available efficiencies. The turbine inlet temperatures are 1740°F and 1800°F.
Increasing Part-Load Fuel Efficiency

The gas turbine shown in Figure 2 operates in a conventional positive pressure cycle. Ambient air is pulled into the compressor and hot exhaust gases are discharged out of the recuperator. Figure 6 shows the same components operating in both a positive pressure and a subatmospheric mode. Note that an intercooler has been added to the subatmospheric version to reduce the temperature at the compressor inlet.

![Diagram showing positive pressure and subatmospheric pressure cycles]

The compressor inlet pulls a vacuum in the hot side of the recuperator and the intercooler. The outlet discharges into the atmosphere. Ambient air flows into the cold side of the recuperator, then through the combustor and through the turbines into the vacuum. Again the gas producer turbine drives the compressor and the power turbine drives the output shaft through a reduction gearbox.

In the 1970s The Garrett Corporation built several subatmospheric gas turbines rated at 12 hp. The rationale was that by operating the combustor at or below atmospheric pressure, natural gas could be burned as a fuel without the need for a fuel-gas compressor. Operating this way meant that the compressor and turbine wheels could be larger and thus more efficient.

With identical rotor groups, the mass flow in the subatmospheric cycle is lower than that of the positive pressure cycle by a factor equal to the pressure ratio. Thus the available power is also reduced by a factor equal to the pressure ratio. If the pressure ratio were 3.25, the mass flow and power output would be 3.25 times lower. If a gas turbine could switch between positive pressure and
subatmospheric pressure, it could offer at 1/3.25 or 31% load almost the same efficiency as it does at full load.

Thermodynamically, the positive pressure and the subatmospheric pressure cycles have the same efficiency except for four considerations. 1/ The compressor inlet temperature has been increased slightly. 2/ As fuel has been added, the compressor must now compress the mass of both air and combustion products. 3/ The added intercooler imposes a pressure drop. 4 / Because of the reduced mass flow, the recuperator is more effective and has a lower pressure drop.

From another perspective, the performance in the subatmospheric gas turbine at sea level is essentially the same as the positive pressure gas turbine operating at an altitude of 29,000 feet. This presumes a pressure ratio of 3.25. If there were two stages of compression, each with a pressure ratio of 3.25, the subatmospheric gas turbine at sea level would have the same performance at sea level as a positive pressure gas turbine operating at 54,000 feet, that is 3.25 x 3.25 less.

By adding valves so that the gas turbine can transition between three pressure levels and thus three mass flows, the gas turbine can offer almost the same efficiency at medium and low loads as it does at full load.

Figure 7 shows the gas turbine operating in the conventional positive pressure, high power mode where ambient air enters the inlet to the low pressure compressor. The three-way valves are shown with heavy black arrows.
Figure 8 shows the gas turbine operating in a transatmospheric mode where one gas-producer rotor is in positive pressure and one is in subatmospheric mode. Ambient air enters the gas turbine at the inlet to the interstage intercooler although it could enter at the inlet to the high pressure compressor. Assuming pressure ratios of 3.25:1 for each compressor, close to full load efficiency can be achieved at 31% power.

Figure 9 shows the gas turbine operating in a fully subatmospheric mode where ambient air enters the cycle at the inlet to the cold side of the recuperator. With two 3.25:1 compressors, the mass flow and power at full rpm and temperature are now $3.25 \times 3.25$ times lower or 9.5% of 100% power in the positive pressure mode. Yet the efficiency should be close to that of the gas turbine operating in the conventional positive pressure mode.
Table 1 summarizes the maximum power available in each of the three modes for a typical application.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Positive Pressure</th>
<th>Transatmospheric</th>
<th>Subatmospheric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum cycle pressure</td>
<td>3.25 x 3.25 atm.</td>
<td>3.25 atm.</td>
<td>1 atm.</td>
</tr>
<tr>
<td>Equivalent altitude</td>
<td>Sea level</td>
<td>29,000 feet</td>
<td>54,000 feet</td>
</tr>
<tr>
<td>Relative mass flow</td>
<td>1</td>
<td>0.31</td>
<td>0.09</td>
</tr>
<tr>
<td>Maximum power</td>
<td>100%</td>
<td>31%</td>
<td>9.5%</td>
</tr>
<tr>
<td>Application</td>
<td>Accelerate or climb hills</td>
<td>Cruise</td>
<td>Stopped, auxiliary power only</td>
</tr>
</tbody>
</table>

Table 1

Thermal and Mechanical Shock

There should be no thermal shock, even when going from 9.5% power to 100% power, as there is no temperature change during transitions between pressure modes. Correspondingly, there should be no mechanical shock as there is no change in rpm. As the power change will be abrupt, however, it will be necessary to design a responsive fuel control and perhaps variable geometry for smoother operation.
Response Time

It is expected that the transition between any one of the three modes should take less than fifty milliseconds. Essentially, it is the time the valves require to actuate, the time the air takes to flow through the gas turbine and the time required for the fuel flow to change. With no change in rpm, the rotor group requires no time to accelerate or decelerate.

The Agile gas turbine could also be used to power a generator for an electric drive application using the power for propulsion and/or other electric loads. For example, it could operate at 9% power in silent watch and yet be at medium power or at full power in fifty milliseconds.

Starting

Ease of starting is an important consideration. There are several approaches. Starting would be done in the subatmospheric mode to reduce the amount of start-up power required. Putting a small motor on the high-speed rotor group and using an inverter to power it would be fairly easy. This motor could also operate as a generator providing auxiliary electric power. Another approach would be to use a blower to blow in through the recuperator in the subatmospheric mode.

Reducing Cost

The rotor groups in the gas producer section are familiar components. They are essentially turbochargers with high efficiency wheels, a diffuser and a turbine nozzle. The intercooler is a readily-available turbocharger intercooler. The techniques for low cost mass production of these components are well known. The use of separate rotor assemblies To eliminate the complexity of having concentric rotors as is commonly done in dual-rotor aircraft engines, separate turbocharger like rotors would be used. It also simplifies the entry and exit of the gases. All of the valves are in the colder section of the gas turbine.

Loss of Load

Any gas turbine can experience a sudden loss of load. When operating at high power In the Agile concept, there would be an instant transition to subatmospheric mode reducing the power to be dissipated by a factor of eleven.

Multiple Uses

The Agile multi-pressure gas turbine is ideally suited for both military and civilian applications. It offers great advantages in fuel economy wherever there is extensive idling or part load operation and yet where full power must be available quickly. Military vehicles, vehicles with high auxiliary loads, buses, trash trucks and delivery trucks used by Federal Express, UPS and the post office are ideal applications. Most of the time, they are idling or need limited or medium power.
But they must have full power available for accelerating, passing and hill climbing. SUVs and other passenger cars face the same challenges.

Intellectual Property

U.S. Patents 6,526,757 and 6,606,864 cover the concept of the multi-pressure gas turbine. They were issued to Robin Mackay on 4 March 2003 and 19 August 2003, respectively.

References

“Practical Vehicular Gas Turbines” was presented at the SAE Future Transportation Technology Conference in Costa Mesa, California in August of 2001. This was the first public disclosure of the multi-pressure concept.

Conclusion

A multi-pressure gas turbine can be developed that offers all of the traditional advantages of a gas turbine with the additional advantages of excellent efficiencies at full, medium and low power demands plus almost instantaneous response time and a cost saving to the nation.

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