Recent Developments in Small Industrial Gas Turbines

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  - Applications
  - History
- Technology
  - thermodynamic trends and drivers
  - core components
- Future requirements
  - Market developments
Gas Turbine as Prime Mover

**Prime mover**: A machine that transforms energy from thermal, electrical or pressure form to mechanical form; typically an engine or turbine.

Gas Turbines vary in power output from just a few kW more than 400,000 kW. The shaft output can be used to generate electricity from an alternator or provide mechanical drive for pumps and compressors.

Siemens Industrial gas turbine range

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Figures in net MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGT5-8000H</td>
<td>375</td>
</tr>
<tr>
<td>SGT5-4000F</td>
<td>287</td>
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<tr>
<td>SGT6-8000H</td>
<td>266</td>
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<tr>
<td>SGT6-5000F</td>
<td>198</td>
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<tr>
<td>SGT5-2000E</td>
<td>168</td>
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<tr>
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<tr>
<td>SGT-800</td>
<td>47</td>
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<tr>
<td>SGT-700</td>
<td>31</td>
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<tr>
<td>SGT-600</td>
<td>25</td>
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<td>SGT-500</td>
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<tr>
<td>SGT-400</td>
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<tr>
<td>SGT-300</td>
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<tr>
<td>SGT-200</td>
<td>7</td>
</tr>
<tr>
<td>SGT-100</td>
<td>5</td>
</tr>
</tbody>
</table>
Industrial Gas Turbine Product Range

Portfolio (MW)

- SGT-800: 47
- SGT-700: 30
- SGT-600: 25
- SGT-500: 17
- SGT-400: 13
- SGT-300: 8
- SGT-200: 7
- SGT-100: 5

Industrial Gas Turbine Product applications

- **Power Generation**
  - An SGT-100 generating set is installed on Norske Shell's Troll Field platform in the North Sea.

- **Pumping**
  - Thirty SGT-200 driven pump sets on the OZ2 pipeline operated by Sonatrach, Algeria.

- **Compression**
  - Two SGT-700 driven Siemens compressors for natural gas liquefaction plant owned by UGDC at Port Said, Egypt.

- **CHP**
  - An SGT-800 CHP plant for InfraServ Bavernwerk’s chemical plant in Gendork, Germany.

- **Comb. Cycle**
  - Two SGT-400 generating sets operating in cogeneration/combined cycle for BIEP at BP’s Bulwer Island refinery, Australia.
Gas Turbine Refresher
Comparison of Gas Turbine and Reciprocating Engine Cycle

Gas Turbine Characteristics

**Size and Weight**
- High power to weight ratio giving a very compact power source

**Vibration**
- Rotating parts mean vibration-free operation requiring simple foundations

**Emissions**
- Very low emissions of NOx

**Operation and Maintenance**
- No Lubricating oil changes
- High levels of availability

**Fuel flexibility**
- Dual fuel capability
- Burn Lean gases (high N2 or CO2 mixtures)
- Varying calorific values

Gas Turbine as Prime Mover

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Energy Sector
Brayton Cycle

**Idealized Brayton Cycle**

1-2 Air drawn from atmosphere and compressed
2-3 Fuel added and combustion takes place at constant pressure
3-4 Hot gases expanded through turbine and work extracted

(in single shaft approx 2/3 of turbine work is used to drive the compressor)

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Ideal Engine Cycle: Efficiency

Simple cycle efficiency = \( 1 - \left( \frac{1}{\frac{P_1}{P_2}} \right)^{\frac{n-1}{n}} \)

Cycle efficiency is therefore only dependant on the cycle pressure ratio.

Assumption: Ideal cycle with no component or system losses.
Deviation from Ideal Cycle
- Aerodynamic losses in turbine and compressor blading
- Working fluid property changes with temperature
- Pressure losses in intakes, combustors, ducts, exhausts, silencers etc.
- Air used for cooling hot components
- Parasitic air & hot gas leakages
- Mechanical losses in bearings, gearboxes, seals, shafts
- Electrical losses in alternators

‘Real’ Efficiencies
- Practical simple cycle gas turbines achieve 25 to 40% shaft efficiency
- Complex gas turbine cycles can achieve shaft efficiencies up to 50%
- However, heat rejected in the exhaust can be used:
  - Large combined cycle GT can achieve close to 60% shaft efficiency
  - Cogeneration (Heat and Power) can exceed 80% total thermal efficiency

Energy Cost Savings
GT cycle parameter study

Increase Pressure ratio and firing temperatures for higher simple cycle efficiencies
Design Drivers:
Low Specific Fuel Consumption

Higher Pressure Ratios
- Increased Cycle Efficiency
- Increased number of compressor / turbine stages and therefore cost

Complex Cycles
- Increased Cycle Efficiency and/or Specific Power
- Can impact operability, cost and reliability

Higher Firing Temperature
- Requires increased sophistication of cooling systems
- Can impact life and reliability and combustor emissions

Design Drivers:
Availability, Cost and Emissions

- High reliability.
  - Moderates the trend to increase firing temperature and cycle complexity.

- Low Emissions (Driven by environmental legislation)
  - More difficult to achieve with high firing temperatures and combustion pressures

- Lowest possible cost.
  - Encourages smallest possible frame size, i.e. high specific power ⇒ high firing temperature.
  - Reduced Pressure ratios (< 20:1) to avoid auxiliary fuel compression costs

Compromise is required in the concept design to get the best balance of parameters
Core Engine Trends:
Key Parameter Trends

![Graph showing Key Parameter Trends]

Engine Trends:
Thermal Efficiency

![Graph showing Thermal Efficiency]

Dramatic impact of increased TET and pressure ratio over last 25 years:
- Specific Power increased by almost 100%
- Specific Fuel Consumption reduced by over 30%
- reduced airflow for a given power output and has resulted in smaller engine footprints, reduced weight and reduced engine costs
### Product Evolution

**SGT-300**
- Introduced 1995
- 7,900 kW(e) 30.5% eff

**TA**
- Introduced 1952
- 750 kW 17.6% eff
- Developed to 1,860 kW

### Gas Turbine Layout

**- single shaft or twin shaft**

**Single Shaft**
- Expansion through a single series of turbine stages.
- Power transmitted through rotor driving the compressor and torque at the output shaft

**Twin Shaft**
- Expansion over 2 series of turbines.
  - Compressor Turbine (CT) provides power for compressor
  - Useless output power provided by free Power Turbine (PT)
SGT-400 Industrial gas turbine

Combustion system

Gas Generator Turbine

Power Turbine

Combustion
## Environmental Aspects

### Pollutants and Control

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Effect</th>
<th>Method of Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>Greenhouse gas</td>
<td>Cycle Efficiency</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>Poisonous</td>
<td>DLE System</td>
</tr>
<tr>
<td>Sulphur Oxides</td>
<td>Acid Rain</td>
<td>Fuel Treatment</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>Ozone Depletion</td>
<td>DLE System</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>Poisonous</td>
<td>DLE System</td>
</tr>
<tr>
<td>Smoke</td>
<td>Visible pollution</td>
<td>DLE System</td>
</tr>
</tbody>
</table>

**DLE - Dry Low Emissions**

## Exhaust Emission Compliance

**Emissions control:**
- Two types of combustion configuration need to be considered:
  - Diffusion flame
  - Dry Low Emissions (DLE or DLN) using Pre-mix combustion

**Diffusion flame**
- Produces high combustor primary zone temperatures, and as NOx is a function of temperature, results in high thermal NOx formation
- Use of wet injection directly into the primary zone to lower combustion temperature and hence lower NOx formation

**Dry Low Emissions**
- Lean pre-mixed combustion resulting in low combustion temperature, hence low NOx formation
- With good design and control <25ppm NOx across a wide load and ambient range possible
Flame temperature affects thermal NOx formation.

Flame Temperature as a function of Air/Fuel ratio:
- Lean burn
- Diffusion flame reaction zone temperature
- Lean Pre-mixed (DLE/DLN)
- Diffusion flame

Lean Pre-mix and Lean burn have lower NOx formation rates compared to a diffusion flame.
Combustor Configuration

**NOx product is a function of temperature**

**Diffusion Combustion**
- high primary zone temperature

**Cooling**

**Dry Low Emissions Combustion**
- low peak temperature achieved with lean pre-mix combustion

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**DLE Lean Pre-mix Combustor**
(SGT-100 to SGT-400 configuration)

- Robust design involving no moving parts
- Fixed swirler vanes
- Variable fuel metering via pilot and main fuel valves

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Energy Sector
Lean Pre–Mix combustion

- Simple fuel system
  - Variable fuel metering via pilot and main fuel valves

- Low NOx across a wide operating range of load and ambient conditions

Combustion DLE Lean Premix System

Key to success

- Good mixing of fuel and air
  - Multiple injection ports around swirler

- Long pre-mix path
  - Fuel injection as far from combustion zone as possible

- Good air flow distribution
  - Can annular arrangement with top hats

- Use of pilot burner
  - CO control & flame stability

- Use of guide vane modulation/air bleed
  - Air flow management
DLE System: Siemens experience

- 15 million operating hours across the range (SGT-100 to SGT-800)
- Approximately 1000 DLE units
- About 90% of new orders DLE

Experience
Stable load accept/reject

Daily profile for unit running more than 8000hrs DLE operation on liquid fuel.

Daily variations
Load Shed and Accept
Gas Fuel Flexibility

- **Biomass & Coal Gasification:**
  - Landfill & Sewage Gas
  - Offshore lean Well head gas
  - Offshore rich gas

- **High Hydrogen Refinery Gases:**
  - Medium Calorific Value (MCV)
  - High Calorific Value (HCV)

- **Other gas:**
  - Associated Gas

- **SIAM Diffusion Operating Experience:**
  - Siemens DLE Units operating
  - DLE Capability Under Development

- **Pipeline Quality NG:**
  - Low Calorific Value (LCV)
  - Medium Calorific Value (MCV)
  - High Calorific Value (HCV)

- **Wobbe Index (MJ/Nm³):**
  - 10 20 40 50 60 70

- **Gas Types:**
  - CO₂ or N₂ content of UK Natural Gas
  - Medium CV Fuel Range Definition
  - LCV Burner

- **CO₂**
  - 0 5 10 15 20 25 30 35 40 45 50

- **N₂**
  - 0 10 20 30 40 50 60 70 80 90 100

- **UK Natural Gas**
  - 0 5 10 15 20 25 30 35 40 45 50

- **LCV**
  - 0 10 20 30 40 50 60 70 80 90 100
Examples of Siemens SGT Fuels Experience

NON DLE Combustion
- Natural Gas
- Wellhead Gases
- Landfill Gas
- Sewage Gas
- High Hydrogen Gases
- Diesel
- Kerosene
- LPG (liquid and gaseous)
- Naphtha
- Wood or Synthetic Gas
- Gasified Lignite

- DLE experience on Natural Gas, Kerosene and Diesel
- DLE on fuels with high N2 and CO2 content.
- DLE Associated or Wellhead Gases

Gaseous Fuel Range of Operation

Turbine
Aerodynamic optimised design!

Minimised loss
- optimum pitch/width ratio across whole span.
- low loading
  - High speed
  - high stage number
- low Mach numbers
- thin trailing edges
- low wedge angle
- zero tip clearance

Aerodynamics
High Load Turbine

Computational Fluid Dynamics (CFD) used to complement experimental testing of advanced components.
Analytical optimised design!

Reduce blade stresses
- Minimal shroud
  - shroud may still be desirable for damping purposes.
- High hub/tip area ratio
- Low rotational speed.

Maximise life
- Low temperatures
- Low unsteady forces

Mechanical Design -

Improved analysis software (grid and solver) and improved hardware allow traditional 'post-design' to be carried out during design iterations.

Meshing of complex cooled blade could take many man months in early 90’s - now down to minutes.

More sophisticated analysis for detailed lifing studies still required after design.
Fatigue Life of Rotating Blades

**Positions of Concern**

- Blade Vibration response
  - Predicted by FE and measured in Lab.
  - Identifies critical blade frequencies and modes (Campbell Diagram)

- High Cycle Fatigue
  - Fillet Radii between aerofoil & platform
  - Top neck of firtree root

- Low Cycle Fatigue
  - In areas of highest stress
  - Eg - blade root serrations

**Mechanical Design - Vibration analysis**

- Campbell Diagram for LPT Blade (Blade only)
  - Engine Speed (rpm) vs Frequency (Hz)
  - Modes 1 to 6 shown

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Cooling optimised design !!

Large LE radius
- minimise stagnation htc
- thick trailing edge thickness and large wedge angle for cooling
- thickness distribution to suit cooling passages.
- Minimise gas washed surface.

Cooled Blading Designs
SGT100 > SGT300 > V2500 Aeroengine
**SGT400 First Vane Cooling Features**

- **Cast 2 Vane Segment**
- **Impingement Cooling**
- **Film Cooling**
- **Turbulators**
- **Trailing Edge Ejection**

**SGT-400 13MW Industrial Gas Turbine**

First Stage Cooled Vane

- Hot Blades are life limited.
  - Oxidation
  - Thermal fatigue
  - Creep

- Life typically 24,000 hrs.
- Life can be increased or decreased depending on duty and environment.
SGT-300 First Stage Cooled Rotor Blade

Ceramic Core forming Cooling Passages

SGT300 8MW Industrial Gas Turbine Multi-Pass Cooled First Stage Rotor Blade

HP Turbine Blade Coatings

Hot Gas Surface Coatings for Corrosion & Oxidation protection
- Aluminide,
- Silicon Aluminide (Sermalloy J)
- Chromising
- Chrome Aluminide, Platinum Aluminide
- MCrAlY

Internal Coatings on Cooled Blades operating in poor environments

Ceramic Thermal Barrier Coatings
- Yttria stabilised Zirconia
- Plasma Spray Coatings used on Vanes
- EBPVD Coatings used on rotating blades
- More uniform structure for improved integrity
Turbine Validation Process

Design → Analysis → Prototype → Test

Assess evaluation and calibration of methods

New technology incorporated into existing engine platforms

SGT-100 Product Development

New ratings have been released

Aerodynamic modifications to compressor and turbine.

Power generation, 5.4MWe
(launch rating 3.9MW previously 5.2SMWe)

Mechanical Drive, 5.7MW
(previous 4.9MW)
The Gas Turbine Package

In addition to the main package, the following is also required:

- Combustion air intake system
- Gas turbine exhaust system
- Enclosure ventilation system (if enclosure fitted)
- Control system
- UPS or battery and charger system

SGT-300 Industrial gas turbine
Package design – The latest Module Design

- Available as a factory assembled packaged power plant for utility and industrial power generation applications
- Easily transported, installed and maintained at site
- Package incorporates gas turbine, gearbox, generator and all systems mounted on a single underbase
- Preferred option to mount controls on package, option for off package.
- Common modular package design concept
- Acoustic treatment to reduce noise levels to 85 dB(A) as standard (lower levels available as options)
Typical Compressor Set

SGT-400
New Package Design

- Minimised customer interfaces reducing contract execution/installation costs
- Highly flexible modular construction
- Customer configurable solutions based upon pre-engineered options
- Standard module interfaces to allow flexibility and inter-changeability
- Additional functionality provided dependent upon client needs
- Base design provides common platform for on-shore and off-shore PG and MD
Future Trends
- guided by market requirements

Universal demand for further increases in efficiency and reliability, and reduction in cost.

Oil & Gas (Mech drive and Power Gen)
- Fuel flexibility - associated gases, off-gases, sour gas
- Remote operation
- Emissions - inc CO2

Independent Power Generation
- Fuel flexibility - syngas, biofuels(?), LPG
- Flexible operation - part load operation
- Distributed cogeneration (rather than centralised generation)
- Emissions - inc CO2
Oil and Gas
remote operations / fuel flexibility

• First application of its kind in Russia (Western Siberia) burning wellhead gas which was previously flared
• Solution:
  Three SGT-200 gas turbine
  • Output 6.75 MWe each
  • DLE Combustion system
  • Guaranteed NOx and CO emission levels of 25ppm
  • Min. air temp. (-57°C)
  • Max. air temp. (+34°C)
• Gas composition with Wobbe Index >45MJ/m³
• Total DLE hours approximately 22,300 hours for each unit
• Significant reduction of emissions: 80-90% reduction of NOx level
• Siemens has supplied 135 gas turbines for Power Generation, Gas compression and pumping duty throughout the Russian oil & gas industry

Power Generation
re-emergence of cogeneration

WATER
FUEL
POWER OR DRIER
PRODUCT / STEAM
GRID

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Energy Sector
Thank You