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Integrated Project

Sustainable energy systems

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Gas Turbines Power Plants up to 2020

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Contribution à RENEW :

Chemin de développement proposé pour des turbines à gaz de 5 MWe à 50 MWe en 2020

HP-1D/06/007/A

Documents associés :

Résumé : Dans le cadre du projet Européen RENEW, pour la simulation des procédés et leur évaluation technique, la définition des paramètres techniques des turbines à gaz à l'horizon 2020 est nécessaire. Certains paramètres ont été défini dans un premier scénario qui présente les rendements de composants mais il manque les principaux paramètres de cycle.

En se référant aux machines existantes, aux délais de développement d'une nouvelle technologie et à celles qui sont déjà en développement, cette note propose un chemin de développement pour les turbines à gaz de puissance comprise entre 5 et 50 MW de façon à cerner leur potentiel en rendement en 2020.

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Contribution to RENEW :

Proposal for a road map on 5 MWe to 50 MWe Gas Turbines Power Plants up to 2020

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Related Documents : N/A

Abstract: For the technical assessment and process simulation in the European project Renew, the technical developers need to know the performance figures of gas turbines by 2020. Some technical features have been provided within a scenario paper which addresses compressor and expander efficiencies but not GT cycle as a whole.
Based on the existing hardware, the time to develop new technology, a road map for 5 to 50 MW Gas Turbine development is forecasted for the next 20 years.

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Chemin de développement proposé pour des turbines à gaz de 5 MWe à 50 MWe en 2020

SYNTHESE

Dans le cadre du projet Européen RENEW pour la simulation des procédés et leur évaluation technique, la détermination des paramètres techniques des turbines à gaz à l'horizon 2020 est nécessaire. Certains paramètres ont été définis dans un premier scénario qui présente les rendements de composants, mais il manque les principaux paramètres de cycle. Sur la base de la technologie existante et de celles en cours d'étude qui peuvent être introduites avant 2020, une prévision de chemin de développement pour les turbines à gaz de 5 à 50 MWe est proposée jusqu'en 2020.

Dans ces niveaux de puissance, les turbines à gaz utilisent des compresseurs axiaux et des aubes de turbine de détente à refroidissement avancé. Les plus performantes utilisent des super-alliages coulés en solidification dirigée (cristaux métalliques dans le sens radial) ou même en mono-cristal pour les aérodérivatives. Toutes peuvent fonctionner avec des chambres de combustion à basses émissions polluantes pour satisfaire une réglementation à 25 ppm de NOx. Les turbines industrielles atteignent aujourd'hui un rendement de 36% et les aérodérivatives un rendement de 40 %. Le développement de technologies pour les turbines à gaz est fortement risqué et maîtrisé seulement par les constructeurs. Pour ne pas nuire à la disponibilité des process fortement intégrés de production de bio-carburants, les développeurs n'introduiront a priori que des turbines à gaz éprouvées et disponibles commercialement à l'horizon concerné.

2 types de turbines à gaz pourraient répondre aux besoins des futures unités de production de biocarburants :

- les turbines aérodérivatives avancées, à l'image de la toute nouvelle machine de General Electric de 100MW, la LMS100 à intercooling, qui présente un rendement de 46% en cycle simple. Ce type de technologie peut aisément être adapté à d'autres turbines à gaz de puissance comprises entre 5 et 50 MW avant 2020, avec des rendements en cycle simple de 45 % (5 MW) à 50 % (50 MW).
- Les turbines industrielles, associées à un cycle à vapeur (cycle combiné), sont envisageables pour des puissances supérieures à 20 MW. En 2020, leur rendement en cycle combiné devrait se situer entre 53 % (20 MW) et 57 % (50 MW).

L'amélioration du rendement des turbines à gaz d'ici 2020 sera liée aux évolutions technologiques suivantes :

- Un meilleur système de refroidissement inter-étages de compresseur (de 1 à 1.5 point de rendement);
- Le recours à la combustion séquentielle (1 point de rendement);
- L'augmentation de la température de flamme (de 1 à 1.5 point de rendement pour 50 à 80°C d'accroissement de température de flamme jusqu'à 1430°C).
- L'amélioration des composants (contrôle des jeux radiaux compresseur, …)

Proposal for a road map on 5 MWe to 50 MWe Gas Turbines Power Plants up to 2020

EXECUTIVE SUMMARY

For the technical assessment and process simulation in the European project Renew, the technical developers need to know the performance figures of gas turbines by 2020. Some technical features have been provided within a scenario paper which addresses compressor and expander efficiencies but not GT cycle as a whole. Based on the existing hardware, the time to develop new technology, a road map for 5 to 50 MW Gas Turbine development is forecasted for the next 20 years.

At this power level, gas turbines are fitted with axial compressor and advanced cooling systems for blades or vanes. The most advanced gas turbines use directionally solidified (DS) cast alloys (crystal growth in the radial direction) or even single crystal cast on the aero-derivative gas turbines. All can be run with a Dry Low Emissions combustor to meet the 25 ppm NOx emission requirement. Aero-derivative gas turbines have got today 40% efficiency and industrial ones 36 %. New gas turbines technology is high risk mastered only by the manufacturers. To preserve availability of highly integrated biofuels production process, developers will probably integrate only proven gas turbines, commercially available at the 2020 timeframe.

2 types of gas turbine plants could meet the requirements of future bio-refineries :

- the advanced aeroderivative gas turbines, like the brand new 100 MW inter-cooled General Electric LMS100 which has got an efficiency of 46 % in simple cycle. This kind of technology can easily flow back to the 5 to 50 MW power range before 2020, with simple cycle efficiencies from 45 % (5 MW) to 50 % (50 MW)

- industrial gas turbines, associated to a steam cycle (combined cycle), in the 20-50 MW range. In 2020, efficiencies in combined cycle mode should range from 53 % (20 MW) to 57 % (50 MW)

- ➢ The expected increase in gas turbines efficiency by 2020 is linked to the following technical improvements :
  - o Improved inter-cooling design (1 to 1.5 point efficiency gain);
  - o Sequential combustion (1 point efficiency gain);
  - o Higher rotor inlet temperatures (1 to 1.5 point efficiency gain for 50 to 80°C turbine inlet temperature increase up to 1430°C).
  - o Other components improvements (compressor tip clearance control, …)

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1. Introduction.

The RENEW project investigates different ways to produce biofuels for the transportation sector. Technical and economic performances of the biofuel production processes are assessed for two time frames : the short term “starting point” and the long term “scenario 2020”.

These biorefineries would range between 50 to 500 MW_{LHV}[1] biomass input. They would include power generation systems in the range of 5 to 100 MWe, dedicated to the recovery of side streams such tail gas exhausting the biofuel synthesis reactor.

The objective of this report is to provide data and information to the RENEW technical developers on performances expected in the 2020 time frame for power generation systems involving Gas Turbines.
Gas turbines are among the most expensive pieces of hardware in such power systems. They are the subject of continuous developments : improvements of compressor and expander efficiencies, but also and mainly improvements on the cycle parameters (firing-temperature, compression ratio) and cycle configurations (intercooling, reheat, …).
The report focus on two possible configurations : simple cycle gas turbine – including high efficiency intercooled GTs – and combined cycles (GT + steam cycle) which may appear as the best option for biorefineries operating in baseload.

Based on the existing hardware, the technologies in the pipe, and the duration (and milestones) to develop new technologies, this note tries to forecast a road map for Gas Turbine evolution for the next 20 years in order to get an estimation of there potential by 2020.

2. Status of the technology for 5 MW – 100MW gas turbines.

2.1. Gas turbine evolution history

Gas turbine efficiency is recorded on figure 1 as a function of power in three types of technology :

- Simple cycle industrial gas turbines which efficiency is around 34 – 35 %
- Aero-derivative gas turbine designed with as little changes as possible from an existing aero-engine. Their lower exit temperatures allowed by higher pressure ratios

[1] LHV : Lower Heating Value

for the same turbine inlet temperature makes them more efficient, topping to 40% efficiency in simple cycle.

- Combined cycle where a heat recuperator is fitted at the exhaust of the gas turbine . It feeds a steam turbine which gives more power. Combined cycle efficiency is over 50% for power around 50MW.

The gas turbines in the 10 - 100 MW range are fitted with axial compressor and advanced cooling systems for blades or vanes. Materials are the best in class ones usually DS cast (crystal growth in the radial direction) or even on the aero-derivative gas turbines single crystal cast. All can be run with a Dry Low Emissions combustor to meet the 25 ppm Nox emission requirement.

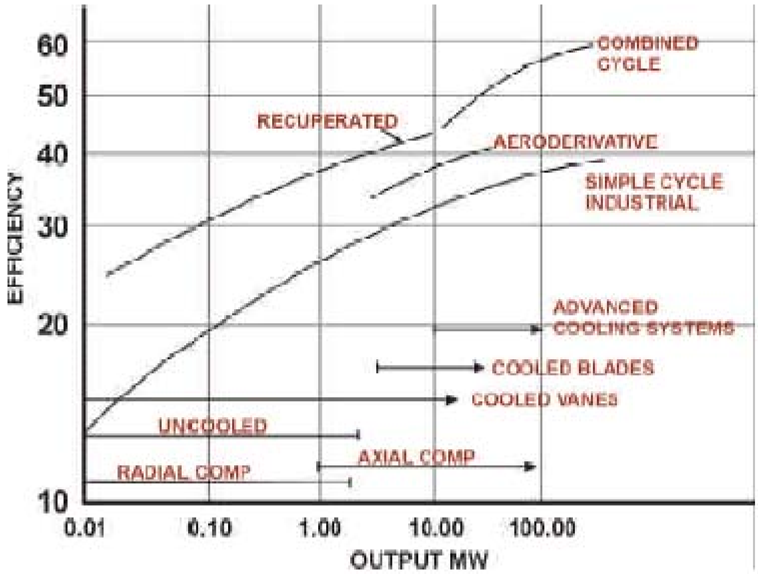


Figure 1: efficiency of different existing gas turbine plants along with power

(from US DoE)

Coming to such efficiencies is based on 50 years of research and developments which can be summarized in figure 2 (from GER 3571H, GER 4250 and GTW 2004/05 handbook). These developments are measured by the increases of the firing temperature up to today levels of 1320 °C to 1420 °C (rotor inlet temperature). The blades are manufactured in a material that melts at such a temperature and so cooling technologies and insulation layers have been mastered by the manufacturers. Dry low Nox combustors have needed more than 25 years of designing to get to today emissions levels. The risk in new Gas Turbine technology is such that only a proven gas turbine can be used on new biomass fed systems : for an exemple GE is offering its IGCC technology with standard “F” class gas turbines and not its brand new “H” class.

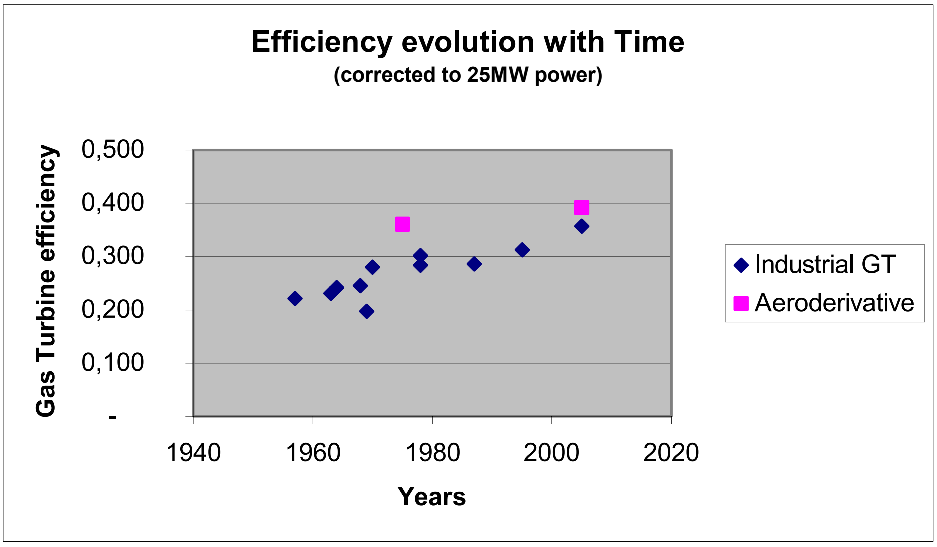


Figure 2: Efficiency improvements for 25MW Gas Turbines

As can be seen on this figure, the improvement in efficiency has been of the order of 0,24% per year since the 50's in industrial gas turbines and 0,1% per year in aero-derivative technology. Traditionally efficiency gains have been made on more powerful gas turbines and when mature, these technologies have flown back to lower power gas turbines as for the GE PG6591C which is fitted with "F" technologies on a PG6551B type of gas turbine: both are producing around 40MW but the "C" has 35,7% efficiency for 31,2% for the "B" version.

Other advanced technologies are proposed like steam cooling for blades and vanes (so called "H" technology) or compressor inter-cooling as featured in the GE LMS100 or the Rolls-Royce WR 21 newest gas turbines.

This report will try to answer two questions :

- What efficiency can be expected on the 5 to 50MW gas turbine in the 2020's?
- How efficient will be the combined cycle power plants fitted with those gas turbines?

2.2. A today technology step : the LMS100

Even if this gas turbine is over the power range of interest for Renew, it features interesting details that will certainly flow into lower power range highly efficient gas turbines.

The 100-megawatt LMS100 represents the first time GE has combined existing components from GE Power Systems' heavy-duty frame gas turbines and GE Aircraft Engines' aero-derivative gas turbines to provide significant gains in gas turbine efficiency.

In simple cycle, the LMS100 has an efficiency of 46 percent. In combined cycle, the efficiency is 54 percent. A key reason for the high efficiency is the use of off-engine inter-cooling technology within the turbine's compression section and a very low exhaust temperature ; The intercooler can give 20 to 30 MW of low grade steam. The turbine exhaust temperatures are quite low in the range of 390 – 430 °C.

The FETT (First Engine To Test) has run for the first time in 2005 and a mature technology can be anticipated for 2011-2012. Rolls-Royce & DCN have tested a more complex 21MW inter-cooled and recuperated gas turbine, the WR21, with an efficiency near 43%.

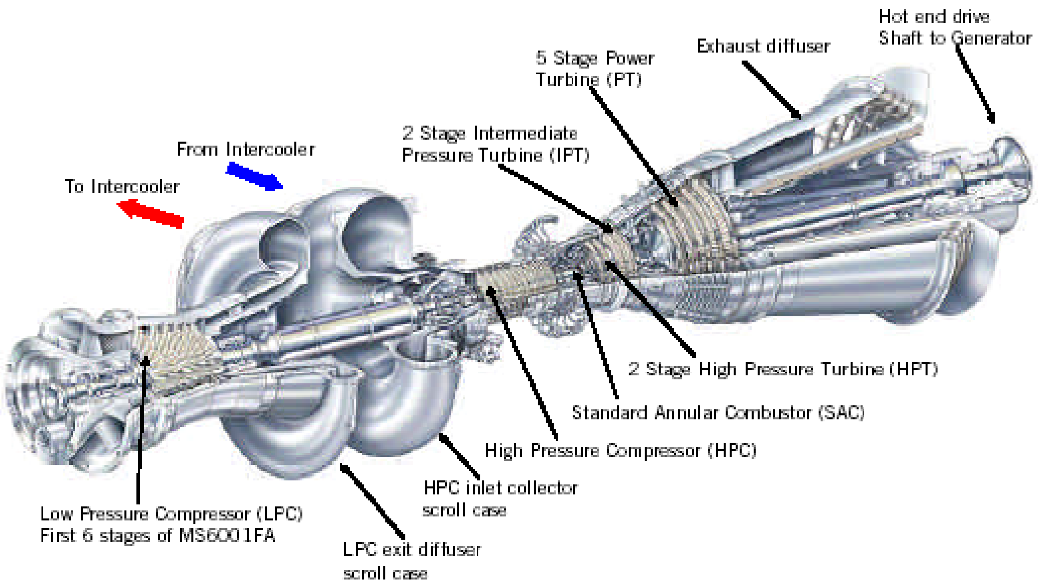


Figure 6 : the GE LMS100

2.3. How long does it take to develop a new technology?

2.3.1. Example of closed loop steam cooled blades

The development time of steam cooling from the first patent before the 80's to a mature technology which can be foreseen after 2010 is around 30 years. After the patents, the first milestone was the launch of a development programme under the ATS programme financed by the DoE of USA : this means that GE had, in 1991, the *capacity to design* with steam cooling technology (Figure 3).

Commercial proposal of the 7/9H gas turbines began in 1994/1995 and Baglan Bay contract was signed in 1996. First tests on site of the 9H happened in 2002 after the Full Speed No Load tests in 2000. GE is now debugging the gas turbine so that it comes to its specifications, phase we expect to be finished around 2010.

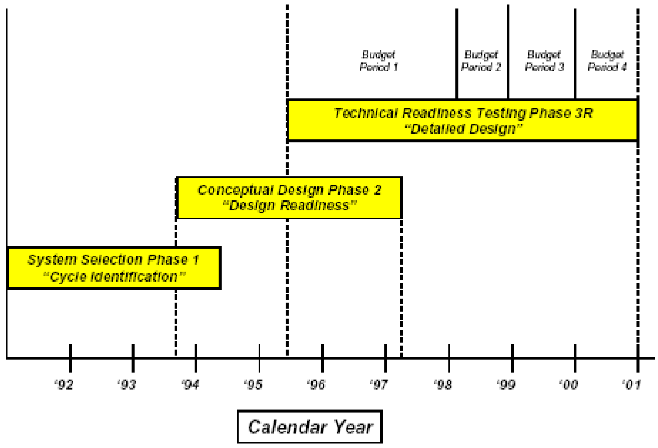
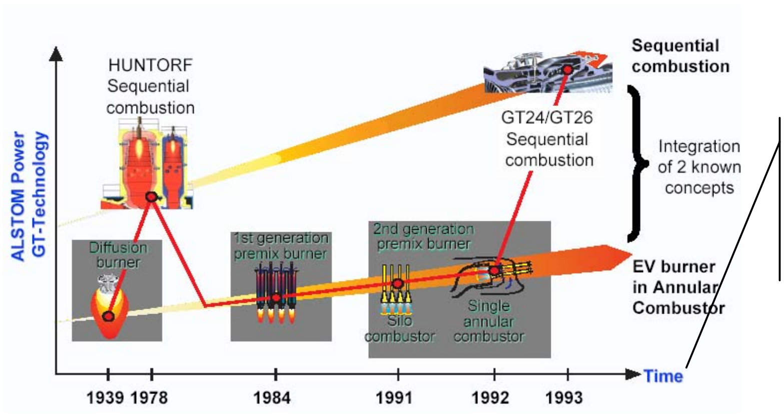


Figure 3 : Plan of 7H gas turbine development

(from GE Advanced turbine system programme 5 Dec 2000)

2.3.2. example of sequential combustion

The development of sequential combustion in Alstom has taken almost the same amount of time in between the early-mid 70's to September 95 where the GT24 was first tested and 2003 where the GT24/26 fleet had most of its drawbacks settled and can be considered as mature. Again 30 years have been needed.



September 1995 :1st test of the GT24

Figure 4 : development of sequential combustion in (ABB) Alstom

2.3.3. Proposed standard development plan

From those experiences and others, a tentative agenda for development of a new technology has been proposed in figure 5. It features 4 phases :

- A research phase to learn how to design the new technology , lasting 10 years;
- An advanced Design phase to select the best design parameters, lasting 3 years ; it ends with the commercial announcement of the new gas turbine;
- A detailed design and manufacturing phase ending with the First Engine To Test, 7 years later;
- A debugging and validation phase : almost 6 years are needed to get a mature gas turbine.

So in 2020, mature gas turbines will use technologies which today are brand new ones proposed in commercial development.

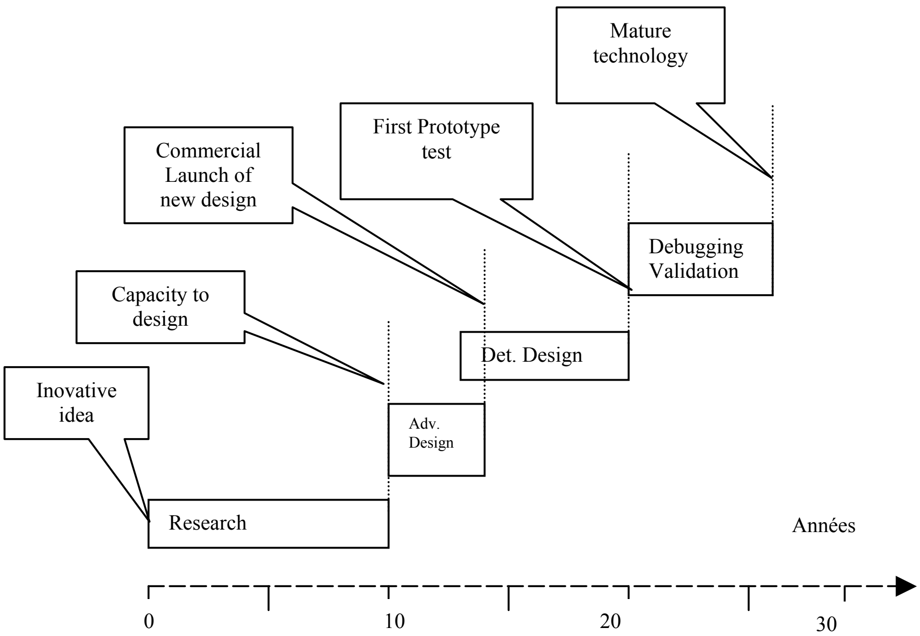


Figure 5 : proposed plan for technology development

3. Which new technologies are being readied?

Many new technologies have been implemented in recently improved gas turbines. They are reviewed and their potential savings estimated as follows :

- <u>Components efficiency through clearances control</u>. Siemens and Mitsubishi have recently on "F" or "G" class gas turbines adapted clearance controls on the turbine sections as well as GE has done it on its "H" technology. Clearances are usually designed for the worst case which is cold casing and hot rotor restart. At design point, clearances are higher than possible which lowers the efficiency. A "good" clearance control system can bring around 0,5% in turbine efficiency. On the compressor, clearance control has been studied for aeroengines but the weight penalty of such a technology has restrained any massive use of it. Same efficiency gain can be forecasted, but the state of development is such that it looks quite difficult to get it on a gas turbine in the 2020's.

- Advanced materials and flame temperature increase. The up to date GE gas turbines in the 40 - 50 MW range are the 6C and LM6000 for respectively heavy duty and aero-derivative gas turbine. Both are using DS cast material facing around 1320°C blade inlet temperature. The LMS100 has already got a 1380 °C blade inlet temperature and still DS (Directionally Solidified) cast blades. Upgrading to Single Crystal cast blade can bring those temperature to the 1420 °C range in the next ten years. Further improvement shall be possible with advanced thermal barrier coatings bringing those temperatures to the 1450°C range. Pressure ratio has to be increased to get the right exhaust temperature : a limit can be met by the last stages compressor blade size. Researches on other new materials won't come to an end in the 2020's. A firing temperature increase of 50°C with the same cooling requirements can bring an efficiency increase up to 1 % absolute value.

- Closed loop air or steam cooling. The "H" technology as GE, Mitsubishi or Siemens have designed it, is still in prototype phase. Steam cooling seems to have a drawback for flexible operation and might be confined to base-load or low cycling plants. The technology back flow from 500MW combined cycle plants will certainly be first on 200-300 MW size before the 5 - 100MW range and will strongly depend on market demand. It seems that a 50MW closed loop air or steam cooled gas turbine won't be ready for 2020 and might appear in 2025.

- Sequential Combustion. For Alstom, sequential combustion is a mature technology which is worth 1 % (absolute value) in efficiency as computed by Bologna University (ASME GT 2002 30558). Other manufacturers have rejected sequential combustion for being an expensive investment, but it can be quite easily fitted on an LMS100 type of gas turbine in between the HP and MP turbines and the still on going efficiency race might impose it as a lower risk development.

- Inter-cooling. During research studies in the 1990's, inter-cooling has been reckoned as the lower risk technology development to get higher efficiency mid size gas turbines. A R&D programme for Flexible Mid-size Gas Turbines was prepared but could not get financial support. So the LMS100 took 10 years more to be proposed and the technology development was slow. Inter-cooling brings a drastic decrease in power consumed by the compressor which is traditionally more than half of the power turbine output. Technology has to be matured, especially with respect to flexible operation, a heat exchanger being always a thermally stressed piece of hardware. Maturity will come in the early 2010's and a 30 to 50 MW new development at 46-

48% efficiency will be launched if the market shows any interest: a commercial success of the LMS100 is the right indicator for it.

- Over-fogging. Fogging is a technology where water is injected as a mist long before compressor inlet so that water vaporisation cools down the air at compressor inlet. It needs injection systems creating very fine droplets so that evaporation time is at shortest. When more water is injected at compressor inlet, water vaporise through the 4-5 first compressor stages and isothermal compression is approached: it is called "over-fogging" and 5% efficiency gain can be estimated through reduced compression power. This technology is employed on many gas turbines to get an increase in power. Then, the efficiency gain is low as the cooling of the air pushes the compressor velocities diagram towards off-design . It is higher risk than the concurrent inter-cooling technology and without any governmental support will not get ready for the 2015's. The LM6000 SPRINT is designed around this kind of technology and field experience has to be reviewed to understand why some operators complain.

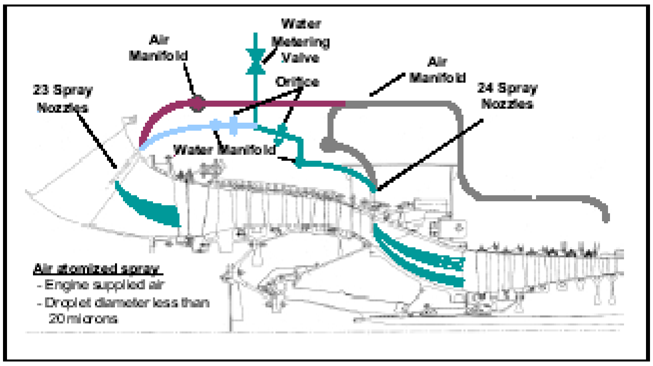


Figure 6 : the GE LM6000 SPRINT system.

4. Improvements in combined cycles

Combined cycle is constituted of a gas turbine which delivers hot gases to a conventional steam cycle composed of a HRSG (Heat Recuperator Steam Generator), a steam turbine and a condenser. Around two third of the power comes from the gas turbine and one third from the steam turbine. Efficiency is dependent on power as shown on figure 1. In the range 20-50 MW, the efficiency is today 50-54%.

As far as the gas turbine delivers the same amount of gases at the same temperature to the steam turbine, any percent efficiency gain (in relative value) due to the gas turbine will improve the combined cycle efficiency by around 0.67 %. Which means that for a gas turbine of 36% efficiency, an increase of 1 point in efficiency will lead to 1 point gain on the associated combined cycle.

Conventional steam cycle is mature technology with some minor improvements still possible on the components which can be valued around 1 % (1 point) combined cycle efficiency gain mainly through better optimised Heat Recuperators Steam Generators.

The major improvement in the steam cycle is the steam temperature (and pressure) which on a combined cycle is given by the exhaust gases temperature. Increasing exhaust temperature lowers the power delivered by the gas turbine, but this power is transferred to the steam turbine. The gas turbine in this case needs less pressure ratio (lower temperature drop in the expander) and so compression work is reduced. The lower air temperature at compressor exit will require more gas to get to the same turbine inlet temperature. From GE, combined cycle efficiency is optimum at a compression ratio around 14 (figure 7). But currently, boiler materials limit the gas turbine exhaust temperature at 600 °C. An increase to 700 °C can only be forecasted after 2020 through the introduction of ultra supercritical (USC) technologies.

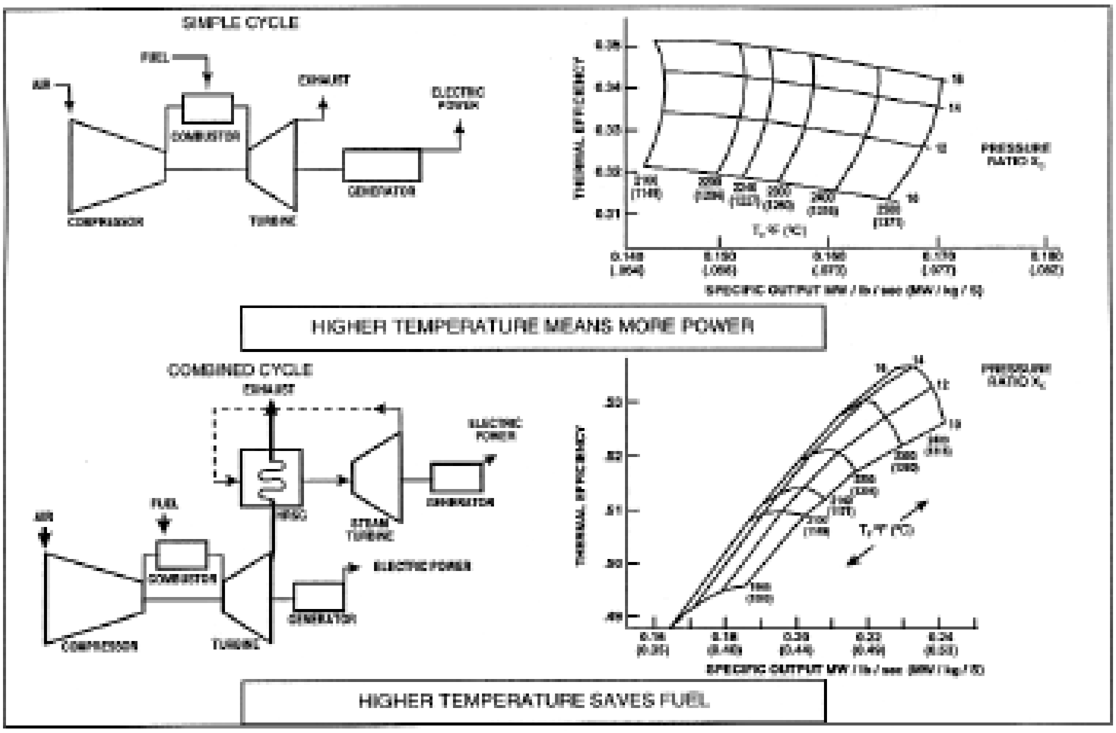


Figure 7 : influence des paramètres de cycle sur le rendement d'après GE mettre en anglais

5. Conclusion.

New gas turbines technology is high risk mastered only by the manufacturers. To preserve availability of highly integrated biofuels production process, developers will probably integrate only proven gas turbines, commercially available by 2020.

Commercial gas turbines by 2015-2020 will feature technologies currently in development. Two types of gas turbine plants could meet the requirements of future bio-refineries :

- the advanced aeroderivative gas turbines, like the brand new 100 MW inter-cooled General Electric LMS100 which has got an efficiency of 46 % in simple cycle. This kind of technology can easily flow back to the 5 to 50 MW power range before 2020, with simple cycle efficiencies from 45 % (5 MW) to 50 % (50 MW).

- industrial gas turbines, associated to a steam cycle (combined cycle), in the 20-50 MW range. In 2020, efficiencies in combined cycle mode should range from 53 % (20 MW) to 57 % (50 MW)

- ➢ The expected increase in gas turbines efficiency by 2020 is linked to the following technical improvements :
  - o Improved inter-cooling design (1 to 1.5 point efficiency gain);
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