Diploma Thesis

Advanced Gas Turbine Cycles: Thermodynamic Study on the Concept of Intercooled Compression Process.

Magdalena Milancej

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Abstract

The General Electric's LMS100, which combines heavy-duty frame and aeroderivative technology, is a first modern production gas turbine system employing off-engine intercooling technology developed especially for the power generation industry. The external intercooler lowers air inlet temperature to the high-pressure compressor, causing its smaller power consumption and lower output temperature, which enables more effective cooling of the hot turbine parts. In the end it results in higher thermal efficiency, which is said to reach 46%.

In the beginning of this diploma thesis the thermodynamic cycle of a gas turbine, its parameters and improvement possibility are presented. A description of the LMS100 and its features follows later.

Subsequently, an analytical study is done to investigate the efficiency improvement by intercooling. The analytical formulae for dimensionless specific work and efficiency are derived and analysed. Next, the LMS100 is modelled by means of the commercial plant performance software GateCycle. The obtained results are presented and analysed.

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Nomenclature

c_p	[J/(kgK)]	Specific heat capacity
h	[J/kg]	Specific enthalpy
H_U	[J/kg]	Lower heating value
$\dot{m}$	[kg/s]	Mass flow rate
n	[-]	Polytropic exponent, parameter
p	[Pa]	Total pressure
Q	[J]	Heat
R	[J/(kgK)]	Gas constant
s	[J/(kgK)]	Specific entropy
T	[°C]	Temperature
ΔT	[°K]	Temperature difference
η	[%]	Efficiency
κ	[-]	Isentropic exponent
v	[m^3/kg]	Specific volume
π	[-]	Compression ratio
ω	[J/kg]	Specific work
θ	[-]	Nondimensional turbine inlet temperature
f	[-]	Portion of cooling air flow
k	[-]	Portion of fuel flow

Subscripts:

C	Compressor
CC	Combustion chamber
f	Fuel
GT	Gas turbine

HPC	High pressure compressor
IC	Intercooler
LPC	Low pressure compressor
p	Polytropic
s	Isentropic
T	Turbine
th	Thermal

Abbreviations:

CC	Combustion chamber
DLE	Dry low emission
GE	General Electric
GT	Gas turbine
HPC	High pressure compressor
HPT	High pressure turbine
IC	Intercooler
IPT	Intermediate pressure turbine
LPC	Low pressure compressor
PT	Power turbine
SAC	Standard annular combustor
STIG	Steam injected gas turbine

1. Introduction

The world is developing very fast and this allows us to be witnesses to the technological progress. Engineers have been working very hard to make good use of their knowledge and available materials to produce efficient, cheap and reliable machines. For the turbomachinery industry this resulted in the recent invention of the scientists from General Electric: LMS100 the first modern intercooled gas turbine system with the amazingly high thermal efficiency of 46% in a simple cycle. This was announced at the end of 2003, but it will begin its commercial operation in mid-2006. The LMS100 is advertised as 'Designed to change the game in power generation', and indeed as one that combines proven technologies from both aeroderivative and heavy-duty gas turbines and also employs off-engine intercooling technologies. It can have a strong influence on the future of this branch of industry. All these features make it very interesting also from the scientific point of view. That is why a study on intercooled compression process and its influence on thermal efficiency is the aim of this diploma thesis.

During the investigation an analytical study was performed showing the potential of efficiency improvement by intercooling. To be more precise the influence of the pressure ratios in different components on the specific work and thermal efficiency was analyzed. For comparison, the LMS100 was modelled by the means of the commercial plant performance software GateCycle. Unfortunately, characteristic data of the gas turbine components are not available so they had to be fixed in advance. The necessary calculations as well as all the plots were done by means of Microsoft Excel 2000.

Firstly, a theoretical description of advanced gas turbine cycles with intercooled compression process and its applications - among others the LMS100 - is given. Further, an analytical study on the thermodynamic cycle with intercooled compression process is performed. The model of the LMS100 within Gate Cycle is presented. A discussion of the obtained results shows the potential of advanced gas turbine cycles with intercooled compression process. At the end, a conclusion on the topic of intercooled advanced gas turbine cycles is done.

2. Description of the LMS100 and its features

The value of production for non-aviation gas turbines is the fastest growing segment of the American industry. Electric power generation gas turbines are the big players in this category and with each year they are gaining a stronger position. The fact that they provide the highest efficiency at the lowest capital cost of any power generation technology available today, as well as extremely low emissions, what is important from the environmental point of view, is working for their success [1].

In 2000 the engineers at GE Energy started developing a new 100MW-class, highly efficient and flexible gas turbine [2]. The effect of 3 years of intensive work occurred to be outstanding. The LMS100 combing frame and aero technology, using intercooled thermodynamic cycle achieves excellent results in both power output and thermal efficiency.

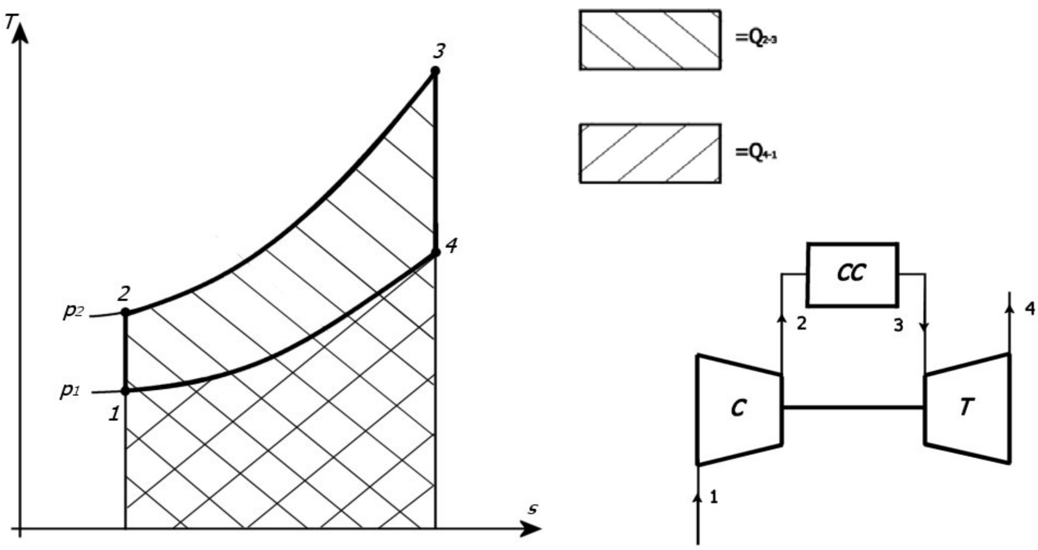
This chapter will introduce the details of the LMS100, bring closer the theory standing behind intercooled gas turbine cycles and give examples of other applications of this thermodynamic solution.

2.1 Description of the thermodynamic process

The conversion of thermal energy to a mechanical one is possible only by means of a thermodynamic cycle. It can be defined as a succession of thermodynamic processes in which the working fluid undergoes a series of state changes and finally returns to its initial state. The character of the thermodynamic cycle, together with its details, influences significantly the design of the engine and its parameters. That is why the relations of the cycle parameters need to be precisely analyzed [3].

2.1.1 The simple gas turbine cycle

The thermodynamic cycle of a simple gas turbine is described by the Brayton-Joule cycle. It consists in the ideal case of four processes: two isentropic and two isobaric ones. In this cycle, depicted in figure 1, the working fluid undergoes an isentropic compression from the state 1 to the state 2. Then it is heated isobarically in the combustion chamber to the state 3. An isentropic expansion leads to the state 4 and an isobaric cooling to the initial state 1. In figure 1 the heat supplied to the cycle in the combustion chamber is denoted as Q_{2-3} and the heat carried away during the process 1-4 as Q_{4-1}.



a) **b)**

Figure 1: a) the ideal simple cycle depicted in the T, s diagram, b) scheme of the open simple cycle [4].

The basic indicator which describes the cycle and which is a measure of its thermodynamic perfection is the thermal efficiency η_{th}. It is the ratio of the amount of energy changed into mechanical energy to the thermal energy supplied to the system:

$$\eta_{th} = \frac{Q_{2-3} - Q_{4-1}}{Q_{2-3}}. \tag{2.1}$$

With the assumption that the processes 1-2 and 3-4 are isentropes between two isobars, the thermal efficiency can be stated as

$$\eta_{th} = 1 - \frac{c_p (T_4 - T_1)}{c_p (T_3 - T_2)} = 1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}, \tag{2.2}$$

where the pressure ratio is $\pi = \dfrac{p_2}{p_1}$.

In reality as a result of different type of losses the thermodynamic cycle looks differently. It can be observed in figure 2. In compression and expansion processes a certain increase in entropy occurs, also heating and cooling are not strictly isobaric, but with certain pressure losses.

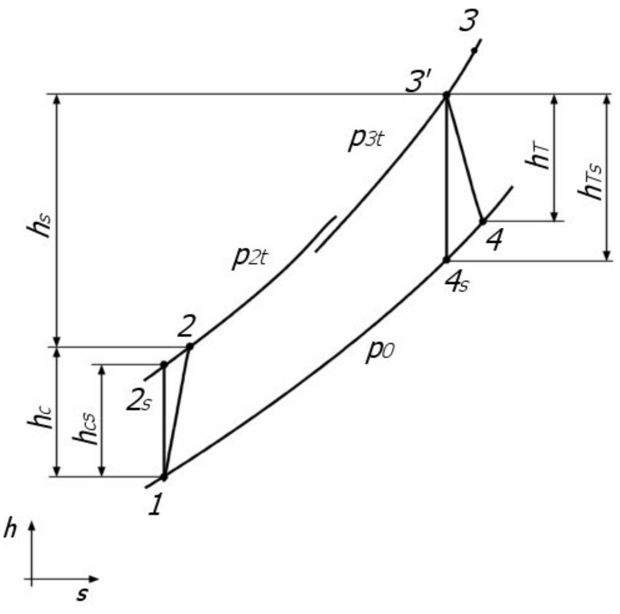


Figure 2: The simple cycle in an h,s diagram including losses.

Formula (2.3) expresses the cycle efficiency by the means of enthalpy and with losses.

This way of representation is very convenient when using an h, s diagram.

$$\eta_{th} = \frac{h_T - h_C}{h_s} = \frac{\eta_{sT} h_{Ts} - \frac{1}{\eta_{sC}} h_{Cs}}{h_s} \tag{2.3}$$

The isentropic efficiencies that have been included into this formula are describing only thermodynamic losses related to the change of the thermal energy to the mechanical one. Other losses resulting from imperfection of other processes like combustion losses, leakage losses or bearing friction losses are neglected here. The isentropic efficiency of a compressor is defined as a ratio of energy that would be transmitted in an ideal process to the energy supplied in a real process:

$$\eta_{sC} = \frac{h_{Cs}}{h_C} \tag{2.4}$$

and the isentropic efficiency of the turbine is equal to:

$$\eta_{sT} = \frac{h_T}{h_{Ts}}. \tag{2.5}$$

The polytropic efficiency is another way of describing losses in compression:

$$\eta_{pC} = \frac{n}{n-1} \cdot \frac{\kappa - 1}{\kappa}, \tag{2.6}$$

where $n < \kappa$ and in expansion processes:

$$\eta_{pC} = \frac{n-1}{n} \cdot \frac{\kappa}{\kappa - 1} \tag{2.7}$$

where $n > \kappa$. These efficiencies as formulae 2.6 and 2.7 shows are dependant only on the exponent n. The polytropic efficiency can be also regarded as isentropic efficiency for a compression or expansion process with a small pressure ratio or in the end as efficiency of one compressor or turbine stage.

2.1.2 Influence of the cycle parameters on its efficiency and other properties

The efficiency of the thermodynamic cycle depends significantly on its parameters. They have to be fixed by a constructor in the very first stage of the design process, as they are closely connected to the engines construction solution. Assuming that θ is a ratio of the turbine inlet temperature and compressor inlet temperature, which in this case is $\theta = T_3/T_1$, it can be stated as:

$$\eta_{th} = \frac{\theta \cdot \eta_{sT}\left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right) - \frac{1}{\eta_{sC}}\left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right)}{\theta - 1 - \frac{1}{\eta_{sC}}\left(\pi^{\frac{\kappa-1}{\kappa}} - 1\right)} \tag{2.8}$$

For analysis of this phenomenon a graphical representation of formula (2.8), which is in fact equation (2.3) transformed under the condition of constant heat capacity c_p, is shown in figure 3.

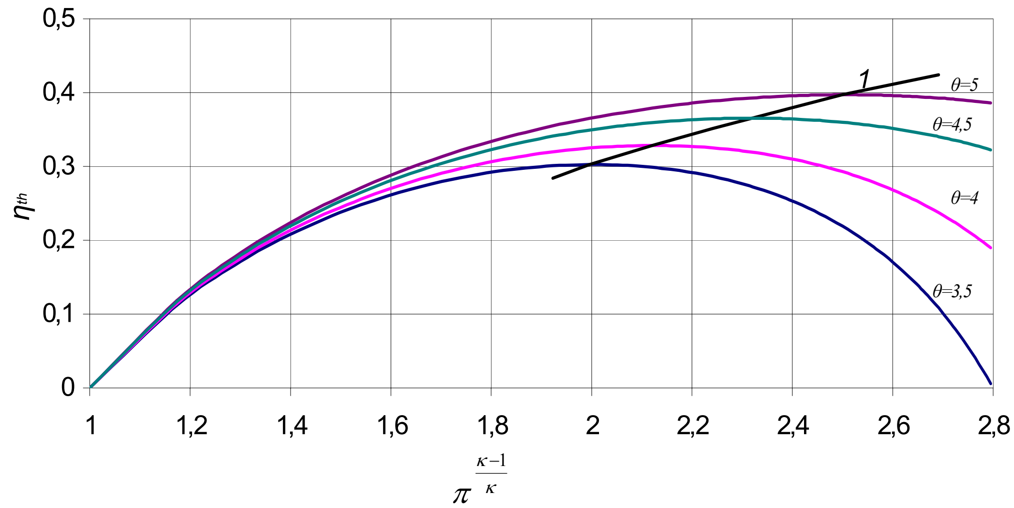


Figure 3: Dependence of the thermal efficiency η_{th} of the cycle on the parameters π, κ and θ for η_{sT}= 0,88 and η_{sC} = 0,86. Line 1 joins points of maximum efficiency for each curve.

Figure 3 represents an exemplary curves for the efficiencies $\eta_{sT} = 0{,}88$ and $\eta_{sC} = 0{,}86$. What can be easily observed is that the thermal efficiency always increases with the increase of the highest temperature of the cycle, which is the turbine inlet temperature T_3. The extension of this parameter, although desirable from the economical point of view, is limited by the heat resistance of the materials. Nevertheless many researches are being done to develop more and more sophisticated materials and to improve blade cooling technologies.

The second parameter that influences the cycle is π. It can be observed in figure 3 that for the constant value of θ , π achieves a maximum. The value of thermal efficiency at the peak point increases with the temperature T_3.

Apart from the mentioned basic parameters the components η_{sT} and η_{sC} have also influence on the efficiency of the cycle. It is obvious that with the growth of the component efficiencies the cycle efficiency increases. Also the optimal compression ratio changes with alteration of η_{sT} and η_{sC}. Greater influence has here the turbine efficiency. The reason for that is the higher enthalpy decrease, which for the same percentage losses means higher absolute values in the turbine than in the compressor.

Independent from the thermal efficiency, an important meaning has also the specific work, which is the amount of work that can be obtained form a unit of working fluid. It is described by the nominator in formula (2.3). The specific work changes with the change of the parameters of the cycle similarly to the efficiency. It increases with the increase of temperature T_3. For a constant T_3 it achieves a maximum for a certain compression ratio, what can be observed in figure 4.

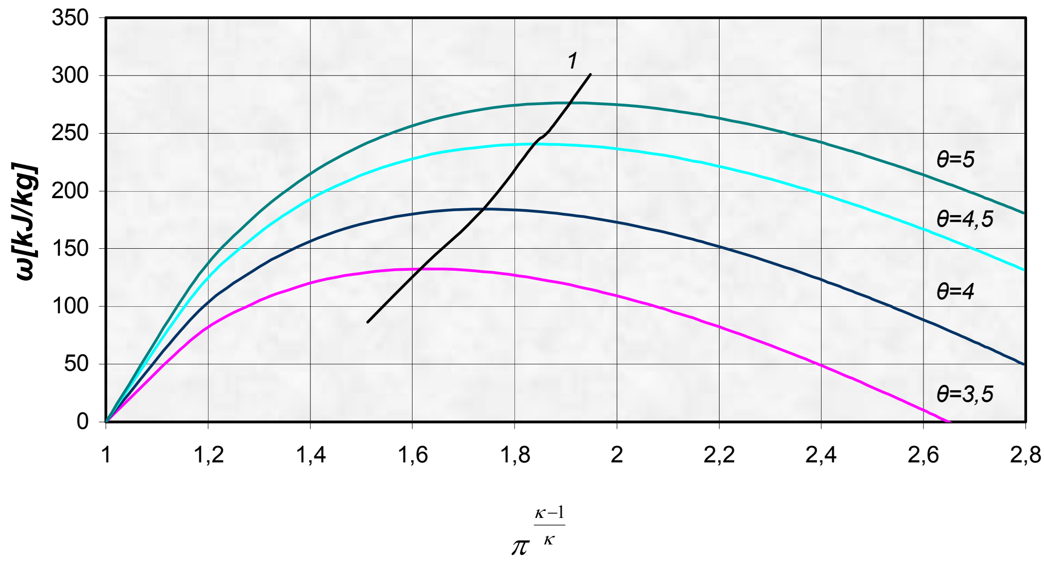


Figure 4: Dependence of the specific work of the cycle on the parameters π, κ and θ for η_T =0,88 and η_C =0,86. Line 1 joins points of maximum specific work for each curve.

The maximum of ω however happens for a lower values of π than the maximum for η_{th} at the same temperature T_3. Therefore, the condition for the highest efficiency does not overlap with the condition for the highest specific work.

The constructor has to decide how the turbine system is going to be designed - taking into account the highest efficiency or the highest specific work. The constructor can also decide that there are more important criteria, like small dimensions or lightness and subject the design and so the choice of the optimum compression ratio to them.

2.1.3 Improvements of the gas turbine simple cycle

The purpose of all improvements that can be introduced into a gas turbine simple cycle is to bring it as close as possible to the Carnot cycle. In the ideal case, the Carnot cycle consists of two isobars and two isotherms and with total heat regeneration it obtains the highest possible efficiency in this range of temperatures. This is called an Ericsson cycle, which is equivalent to the Carnot cycle.

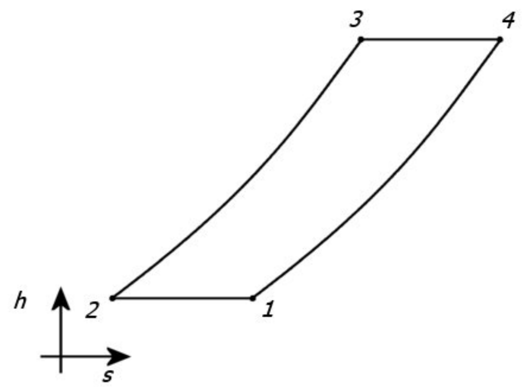


Figure 5: Scheme of the Ericsson cycle

The ways of improving the gas turbine thermal efficiency and so bring it closer to the ideal cycle, result from analytical analysis of the formula (2.3). Simply decreasing the denominator or increasing the nominator would enlarge the final result. The first way can be realised by heat recovery of the exhaust gases, which is especially efficient for low-pressure ratios. The second way can be achieved either by reheated combustion or intercooled compression and these two ways will be described further.

2.1.3.1 The reheated combustion

This process aims to reduce losses of expansion to become possibly close to isothermal expansion process. This can be done by continuous heating of the gas as it expands through the turbine. The continuous heating is not practical and so it is done in stages. In this case, the gases are allowed to expand partially before they enter the combustion chamber, where heat is added at constant pressure until the limiting temperature is reached. The use of reheat increases the turbine work output without changing the compressor work or the maximum limiting temperature. Using the turbine reheat increase the whole cycle output [5].

2.1.3.2 The intercooled compression

Another method of increasing the overall efficiency of a gas turbine cycle is to decrease the work input to the compression process. This effects in an increase of the net work output. In this process the fluid is compressed in the first compressor to some intermediate pressure and then it is passed through an intercooler, where it is cooled down to a lower temperature at essentially constant pressure. It is desirable that the lower temperature is as low as possible. The cooled fluid is directed to another compressor, where its pressure is further raised and then it is directed to the combustion chamber and later to the expander. A multistage compression processes is also possible.

The overall result is a lowering of the net work input required for a given pressure ratio. According to [3] the intercooling is particularly effective when used in a cycle with heat recovery. However, intercooling used without reheating causes decrease of the efficiency at least for small pressure ratios. It is explained by the drop of temperature after the compressor, which is compensated by the increase of the temperature in the combustion chamber.

As this method is the main topic of this diploma thesis, it will be further developed in the next chapters.

2.2 Description of General Electric's LMS100

The General Electric Company is a multinational technology and services company. It is world's largest corporation in terms of market capitalisation. GE participates in a wide variety of markets including the generation, transmission and distribution of electricity, lighting, industrial automation, medical imaging equipment, motors, railway locomotives, aircraft jet engines, aviation services and materials such as plastics, silicones and abrasives.
The market-driven, customer-focused innovations together with technology base and product experience led the company to the development of the LMS100, a new gas turbine system advertised as "Designed to change the game in power generation". The reason for these splendid words as well as other details concerning this new turbine system can be found in the next subchapters.

2.2.1 General Information

The LMS100 is a first modern production gas turbine system employing intercooling technology developed especially for the power generation industry. The designation “LMS” indicates that the engine is a combination of elements from the LM series aeroderivatives produced by GE Transportation’s Aircraft Engines and the MS heavy-frame engines components from GE Energy.

The main driver for the development of the LMS100 was market research conducted by GE that indicated that its customers wanted a gas turbine with the flexibility to operate economically over a wide range of dispatch scenarios. Specific desired characteristics were high efficiency, cyclic capability, fast starts, dispatch reliability, turndown capability, fuel flexibility, load following capability and low emissions. The research indicated that a 100 MW machine would be an ideal power block size. GE chose the intercooled cycle and the union of technology from its Aircraft Engines and Energy divisions to meet these needs.
Figure 6 shows how the LMS100 is competitive on the market in terms of dispatch vs. power output.

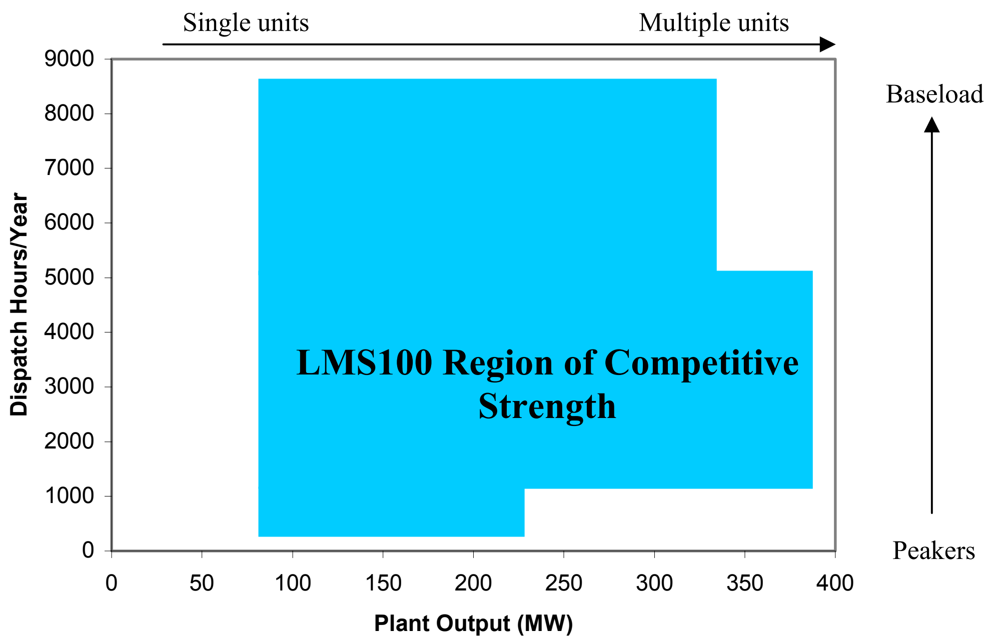


Figure 6: LMS100 – competitive strength in the range of applications

In a simple cycle, the LMS100 has an efficiency of 46%, which is 10% higher than GE's highest efficiency gas turbine on the market today, the LM6000. A key reason for the high efficiency is according to the obtainable information the use of off-engine intercooling technology within the compression section of the gas turbine. In a combined cycle, the efficiency is 54%. It is relatively low what results from the high-pressure ratio of the cycle which leads to a low turbine outlet temperature.

The LMS100 can be used for power generation in simple cycle, combined heat and power and combined cycle applications. In the future it will be available for mechanical drive applications. It offers cycling capability without increased maintenance cost, low lapse rate for hot day power, and a modular design for ease of maintenance and high availability. It can start and achieve full power in 10 minutes and has load following capability. At 50% turndown, the part-power efficiency is 40%. This is higher than most gas turbines at full power in the market today.

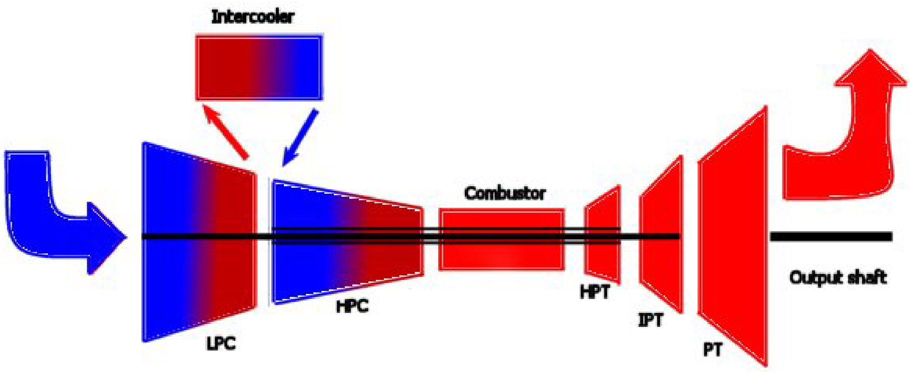


Figure 7: The scheme of the LMS100 [4]

The LMS100 can operate in both 50- and 60-Hertz applications without any need for a speed-reducing gearbox. The aerodynamically coupled or free power turbine is designed to operate efficiently in either frequency by changing the first nozzle row of the power turbine. The power output is said to be in the range of 99-112MW.

The first information about the LMS100 was published at the end of the year 2003. Since then, the work on the LMS100 has been in progress. According to the GE news page the full load test was to be carried out in the first half of 2005. The first production units in the standard annular combustor configuration are expected in the second half of 2005 then in early 2006 the steam injection for power augmentation configuration followed by the dry low emissions version in the second half of 2006.

2.2.2 Development and production

Development of the LMS100 was an international collaboration, which represents a global development and production effort. It is for the first time that GE multiple businesses were not only providing expertise in the development, but also designing, manufacturing, sourcing, assembling and testing the product. Businesses involved with the development and production of the LMS100 are listed below:

- GE's Aircraft Engines (GEAE) Industrial Aeroderivative group of Evendale, Ohio is leading the program and designing the core engine, intermediate turbine frame, power turbine module, core engine control and leading the system engineering and integration efforts, including the intercooling system.

- GE Power Systems Gas Turbine Technology group of Greenville, S.C., is designing the low-pressure compressor, exit and inlet scrolls, power turbine aft shaft system and exhaust diffuser/collector.
- GE Aero Energy of Houston, Texas is designing the engine mounting system, package enclosure, control system software and auxiliary support systems.
- GE Industrial Systems is designing and supplying the control system using its new Mark VIe control system with dual-channel architecture.
- GE Global Research Center is conducting combustion testing and providing technical expertise.
- Avio, S.p.A. in Torino, Italy, is responsible for the design, development, manufacturing and assembly of the intermediate power turbine rotor/stator module and for the design of the power turbine as well as for the manufacturing of a large portion of the power turbine module components.
- Volvo Aero Corporation in Trollhättan, Sweden is designing and manufacturing the PT case and compressor rear frame and manufacturing the IPT frame.
- Sumitomo Corporation of Japan is responsible for the supply of a significant share of production generators.

2.2.3 Design technical data

The cycle design of the LMS100 was based on matching the existing compressor of GE Aero Engines' CF6-80C2 aircraft engine with available GE Energy compressor design. The firing temperature was increased to the point allowed by the cooled high-pressure air to maintain the same maximum metal temperatures as the LM6000 gas turbine. The result is a design compression ratio of 42:1 and a firing temperature class of 1380°C.

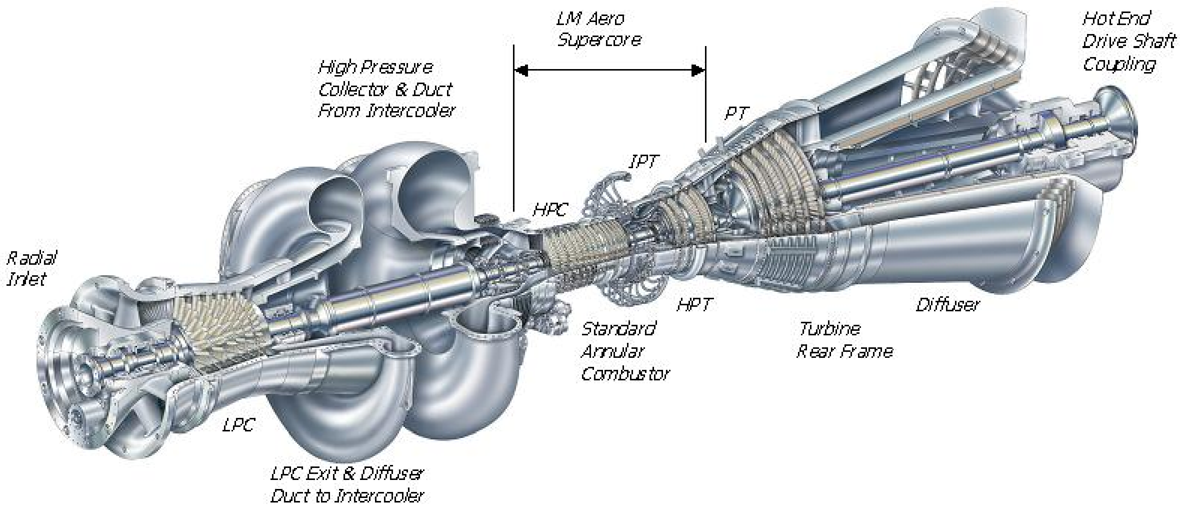


Figure 8: The scheme of the LMS100 engine [7]

The LMS100 engine consists principally of three parts: a low-pressure compressor, aeroderivative “supercore” and a power turbine. Here follows a detailed list of the most important components:

- Low-pressure compressor and inlet are basically the first six stages of the MS6001FA industrial gas turbine’s compressor, with the shape of some airfoils revised. It provides the high airflow capacity required by the LMS100 cycle with operating speed of 5500rpm.
- Intercooler – two designs will be offered, an air-to-water and an air-to-air model for applications where water is not available.
- The high efficiency aerodynamically designed “supercore” consists of:
  - High-pressure compressor based on the CF6-80C2 aircraft engine compressor with the airfoils and casing strengthened for higher pressure ratio condition; consists of 14 stages; operating speed is approximately 9300rpm.
  - Combustor – will be available in two configurations: a single annular combustor with water or steam injection for NOx control, equipped with dual fuel capability and an advanced dry low emissions combustor operating on gas fuel; both designed to achieve 25ppm NOx.

  - High-pressure turbine, a two stage turbine contains the latest airfoil, rotor, cooling design and materials from the CF6-80E1 aircraft engine; the turbine inlet temperature is approximately 1380°C.
  - Intermediate pressure turbine - the two-stage axial turbine driving the LPC through a mid-shaft and flexible coupling is newly designed for this project.
- The third element of the gas turbine is a five-stage aircraft design power turbine that has been specifically designed for the LMS100. The exhaust frame and aft drive shaft are based on a rugged heavy-duty gas turbine exhaust design.
- Generator is dual rated for 50 or 60 Hz applications and available in air-cooled or water-cooled models.

LMS100's IPT drives the LPC through a mid-shaft, which is the same design as the CF6/LM6000 and flexible coupling, which is of the same design as used on the LM2500 marine gas turbine on the U.S. Navy DDG-51 destroyers.

The important feature for the LMS100 is that it can operate at 50Hz and 60Hz without gearbox, which reduces the system complexity. The efficiencies and power output for the 50Hz turbine applications are slightly smaller than for the 60Hz. This difference together with the range of efficiencies and output for the different combustion chamber configuration can be observed in the Table 1.

Model	Output (MWe)		Efficiency (%)	
	50Hz	60Hz	50Hz	60Hz
DLE	99	98,7	45	46
SAC (w/Water)	102,5	102,6	44	44
SAC (w/Steam)	102,2	102,1	47	48
STIG	110,8	112,2	50	50

Table 1: LMS100 ISO performance data: simple cycle gas turbine 50Hz/60Hz applications.

2.3 Other examples of intercooled turbines

The LMS100 is the first modern production gas turbine to employ off-engine intercooling technology in the power generation industry. However, the concept of intercooling is itself not new and was widely used most of all in the marine gas turbine industry. In the following part of this chapter a few other solutions using this technology are described.

2.3.1 General Electric

A precursor to LMS100 was LM6000 Sprint, introduced by GE in 1998, with a brand new spray intercooling system. Sprint - which stands for “Spray Intercooled Turbine” - reduces compressor discharge temperature thereby allowing enhancement of power by 12% at ISO and more than 30% at 32°C ambient temperatures.

The Sprint system is composed of atomized water injection at both low-pressure compressor and high-pressure compressor inlet plenums. This is accomplished by using a high-pressure compressor, eighth-stage bleed air to feed two air manifolds, water-injection manifolds and sets of spray nozzles, where the water droplets are sufficiently atomized before injection at both LPC and HPC inlet plenums.

2.3.2 Rolls–Royce

Rolls–Royce is a global company providing power for use on land, sea and air operating in the civil aerospace, defence, marine and energy markets. The company's core technology and capability is centred on the gas turbine. There are 54,000 Rolls-Royce gas turbines in service almost all around the world [10].

The company has a long history of supplying intercooled and recuperated gas turbines for the marine industry. The first one, named RM60 was developed in the late 1940s. A rather complex engine, which was well ahead of its time, powered the HMS Grey Goose in 1953. This was the world's first solely gas turbine-powered warship and the first attempt to use an intercooled and regenerative cycle to give good fuel consumption across the power range.

Figure 9: HMS Grey Goose [10]

The most recent development of this concept, the intercooled and recuperated WR-21 marine gas turbine developed by Northrop Grumman/Rolls-Royce has been selected to power the Royal Navy's Type 45 D class destroyer. Rated at 25MW, the WR-21 is the first production aeroderivative gas turbine to incorporate compressor intercooling and exhaust heat recuperation technologies that deliver low specific fuel consumption across the engines' entire operating range. The intercooled recuperated cycle combines intercooling and recuperation to the mutual benefit of both. The thermal efficiency loss due to intercooling is offset by increased exhaust heat recovery due to the lower recuperator airside inlet temperature. In the Rolls-Royce WR-21 engine this cycle is combined with the use of variable turbine geometry to deliver high efficiency at low load levels [11].

2.3.3 Pratt & Whitney

Pratt & Whitney (The United Technologies Corp. division) is, after GE and Rolls Royce, a world leader in the design, manufacture and support of military and commercial aircraft engines and space propulsion systems. Commercial air giants Boeing and Airbus are Pratt & Whitney’s largest commercial engine customers; military offerings include engines for the F/A-22, F-15, F-16, C-17 and Joint Strike Fighter.

What is the most important for this thesis is that P&W also makes industrial gas turbines. Thought mainly for marine applications, recently Pratt & Whitney's gas turbines are used to generate electricity in a growing number of locations [8].

Up till now Pratt & Whitney has not produced gas turbine with an intercooled thermodynamic cycle. However, they are taking part in the Next Generation Turbine Program founded by US Department of Energy, which is intended to develop gas turbines for the intermediate load electric power market, with costs lower than any aeroderivatives and efficiencies higher than any current gas turbine, and with the flexibility for rapid starts at least 400 starts per year. Pratt & Whitney's candidate to meet the attributes of the Next Generation Turbine Program is the intercooled gas turbine cycle. The development work is still in progress [9].

3. Analytical study of the thermodynamic cycle

The main point of the thermodynamic study is defining the thermal efficiency η_{th} of the thermodynamic process and specific work ω, as well as investigation of parameters of the cycle: optimal pressure ratios π, component efficiencies and their mutual relations.

This chapter focuses on the analytical study of the intercooled thermodynamic cycle as close to the LMS100 as possible. Firstly, the assumptions used for the further calculations are presented, followed by the derivations of the formulae used for the study, their graphical representation and finally description and analysis.

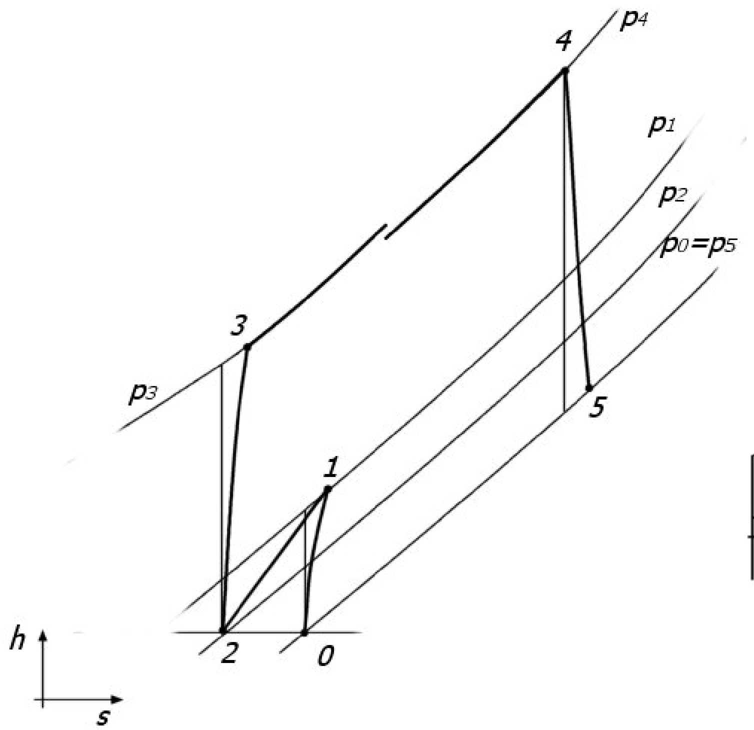
3.1 Assumptions for calculations

It is assumed that the working fluid is a perfect gas and hence for all calculations is valid that:

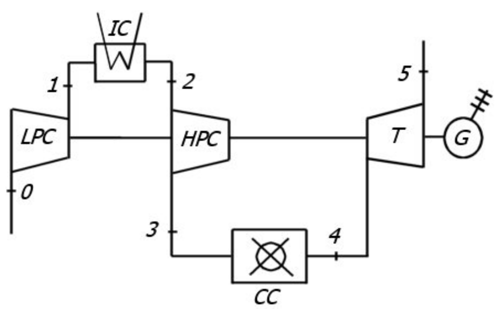
$$p \cdot v = R \cdot T \,. \qquad (3.1.)$$

According to [12] it is convenient to perform initial analysis of cycles assuming that the working fluid is a perfect gas. The calculations then are greatly simplified and the resulting ease of analysis makes it possible to gain a deeper insight into the variations that may be expected from changes in cycle conditions. Final calculations may be done afterwards using real-gas properties in the knowledge that conditions will not be greatly changed.

The diagram of the system, which was analysed, is depicted in figure 9. The system consists of a low-pressure compressor, intercooler, high-pressure compressor, combustion chamber and turbine. In reality the LMS100 operates with 3 different expanders, but for the study splitting of the expansion process into three sub processes is not necessary. The gas turbine is assumed to be isolated and to work in an open cycle with the ambient conditions: T_0=15°, P_0=1bar. Cooling is made with ambient air and it is assumed that the intercooler cools the fluid to the ambient temperature so T_2=T_0. All pressures and temperatures are total, heat capacity is considered to be constant.



a)



b)

Figure 9: a) Intercooled process used in the calculations depicted in the h,s diagram, b) Scheme of the intercooled gas turbine.

The following notations are used:

$$\theta = \frac{T_4}{T_0},\ \pi_{LPC} = \frac{p_1}{p_0}, \pi_{HPC} = \frac{p_3}{p_2}, \pi_T = \frac{p_4}{p_5},$$

Two sets of calculations were performed. The first calculation is done for the ideal case where no pressure losses are taken into consideration so that $p_2=p_1$, $p_4=p_3$. The second includes thermodynamic losses that are considered in the cycle in form of polytropic efficiencies and losses in intercooler and in the combustion chamber defined as:

$$k_{IC} = \frac{p_1}{p_2},\ k_{CC} = \frac{p_3}{p_4}.$$

3.2 The thermodynamic cycle calculations

In order to analyse the turbine system a set of characteristic formulas is presented in this subchapter. The purpose of this investigation is finding the optimal working parameters for the intercooled compression process.

3.2.1 Without losses

In the description of the thermodynamic processes an isentropic curve defined with the following equation is used.

$$p_0 \cdot v_0^{\kappa} = p_1 \cdot v_1^{\kappa}. \tag{3.2.}$$

From formulae (3.1) and (3.2) the specific work of the compressors and the expander can be expressed by:

$$\omega_{LPC} = c_p T_0 \left(\pi_{LPC}^{\frac{\kappa-1}{\kappa}} - 1 \right), \tag{3.3.}$$

$$\omega_{HPC} = c_p T_2 \left(\pi_{HPC}^{\frac{\kappa-1}{\kappa}} - 1 \right), \tag{3.4.}$$

$$\omega_T = c_p T_4 \left(1 - \frac{1}{\pi_T^{\frac{k-1}{k}}} \right). \tag{3.5.}$$

From the energy balance in the combustion chamber

$$\dot{m}_0 c_p T_3 + \dot{m}_f H_U + \dot{m}_f c_{pf} T_f = \left(\dot{m}_0 + \dot{m}_f \right) c_p T_4 + \dot{Q}_L \tag{3.6.}$$

results the equation for the ratio f

$$f = \frac{\dot{m}_f}{\dot{m}_0} = \frac{\theta - \pi_{HPC}^{\frac{\kappa-1}{\kappa}}}{\frac{H_U}{c_p T_0} - \theta}, \tag{3.7.}$$

where $\dot{m}_f$ is the fuel mass flow.

Having described all the components of the cycle its specific work can be stated:

$$\omega_{GT} = \omega_T - \omega_{HPC} - \omega_{LPC}. \tag{3.8.}$$

For the ideal case it is valid that:

$$\pi_T = \pi_{LPC} \pi_{HPC}. \tag{3.9.}$$

For the sake of further investigations the final equation is represented in its dimensionless form and in dependence of two parameters π_T and π_{LPC}. Taking also into account that $T_2 = T_0$ it can be stated:

$$\frac{\omega_{GT}}{c_p T_0} = \theta \cdot \left(1 - \frac{1}{\pi_T^{\frac{\kappa-1}{\kappa}}} \right) - \left(\frac{\pi_T}{\pi_{LPC}} \right)^{\frac{\kappa-1}{\kappa}} - \pi_{LPC}^{\frac{\kappa-1}{\kappa}} + 2. \tag{3.10.}$$

Next, the formula for the thermal efficiency of the cycle follows, also presented in terms of π_T and π_{LPC}:

$$\eta_{th} = \frac{\omega_{GT}}{f \cdot H_U} = \frac{\theta \cdot \left(1 - \frac{1}{\pi_T^{\frac{\kappa-1}{\kappa}}}\right) - \frac{\pi_T^{\frac{\kappa-1}{\kappa}}}{\pi_{LPC}} - \pi_{LPC}^{\frac{\kappa-1}{\kappa}} + 2}{\frac{\theta - \left(\frac{\pi_T}{\pi_{LPC}}\right)^{\frac{\kappa-1}{\kappa}}}{1 - \theta \cdot \frac{c_p T_0}{H_U}}}. \tag{3.11.}$$

In order to represent the efficiencies in a more readable way a new parameter n is introduced. It is defined as:

$$n \in [0,1], \quad \pi_{HPC} = \pi_T^{1-n}, \quad \pi_{LPC} = \pi_T^{n}. \tag{3.12.}$$

This results in:

$$n = 1 \rightarrow \pi_{LPC} = 1; \pi_{HPC} = \pi_T$$
$$n = 0 \rightarrow \pi_{LPC} = \pi_T; \pi_{HPC} = 1$$

In the end the formula for η_{th} versus π_T, n, θ is stated:

$$\eta_{th} = \frac{\theta \cdot \left(1 - \frac{1}{\pi_T^{\frac{\kappa-1}{\kappa}}}\right) - \pi_T^{n \cdot \frac{\kappa-1}{\kappa}} - \pi_T^{(1-n)\cdot\frac{\kappa-1}{\kappa}} + 2}{\frac{\theta - \pi_T^{(1-n)\cdot\frac{\kappa-1}{\kappa}}}{1 - \theta \cdot \frac{c_p T_0}{H_U}}}. \tag{3.13.}$$

The further parametric study of the formulae (3.10) and (3.13) can be found in the chapter 3.3.

3.2.2 With losses included

Based on the assumptions made in the previous chapters, we develop the formulae describing the components of the thermodynamic cycle, including pressure losses in form of polytropic efficiencies and pressure drop coefficients:

$$\omega_{LPC} = c_p T_0 \left(\pi_{LPC}^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pc}}} - 1 \right), \tag{3.14.}$$

$$\omega_{HPC} = c_p T_2 \left(\pi_{HPC}^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pc}}} - 1 \right), \tag{3.15.}$$

$$\omega_T = c_p T_4 \left(1 - \frac{1}{\pi_T^{\frac{k-1}{k}\cdot\eta_{pT}}} \right). \tag{3.16.}$$

From the properties of the combustion chamber results:

$$f = \frac{\theta - \pi_{HPC}^{\frac{k-1}{k}}}{\frac{H_U}{c_p T_0} - \theta}. \tag{3.17.}$$

In the end using the assumed pressure losses it can be stated that:

$$\pi_T = \frac{\pi_{LPC} \cdot \pi_{HPC}}{k_{IC} \cdot k_{CC}}. \tag{3.18.}$$

Finally, the formula for the specific work of the intercooled cycle including losses is as follows:

$$\frac{\omega_{GT}}{c_p T_0} = \theta \cdot \left(1 - \frac{1}{\pi_T^{\frac{\kappa-1}{\kappa}\cdot\eta_{pT}}} \right) - \left(\frac{\pi_T}{\pi_{LPC}} \cdot k_{IC} k_{CC} \right)^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pC}}} - \pi_{LPC}^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pC}}} + 2. \tag{3.19.}$$

Next the formula for thermal efficiency of the cycle follows, also presented in terms of π_T and π_{LPC}:

$$\eta_{th} = \frac{\omega_{GT}}{f \cdot H_U} = \frac{\theta \cdot \left(1 - \frac{1}{\pi_T^{\frac{\kappa-1}{\kappa}\cdot\eta_{pT}}}\right) - \frac{\pi_T}{\pi_{LPC}}^{\frac{\kappa-1}{\kappa}\cdot} - \pi_{LPC}^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pC}}} + 2}{\frac{\theta - \left(\frac{\pi_T}{\pi_{LPC}} \cdot k_{IC} k_{CC}\right)^{\frac{\kappa-1}{\kappa}\cdot\eta_{pC}}}{1 - \theta \cdot \frac{c_p T_0}{H_U}}}. \tag{3.20.}$$

Again the results are represented with respect to n:

$$\begin{aligned} & n \in [0,1], \\ & \pi_T = \frac{p_3}{p_0}, \\ & \pi_{LPC} = \pi_T^n, \\ & \pi_{HPC} = k_{IC} \cdot \pi_T^{1-n}, \\ & \pi_T^t = \frac{\pi_T}{k_{CC}}. \end{aligned} \tag{3.21.}$$

Finally, the equation for the thermal efficiency takes form:

$$\eta_{th} = \frac{\theta \cdot \left(1 - \left(\frac{k_{CC}}{\pi_T}\right)^{\frac{\kappa-1}{\kappa}\cdot\eta_{pT}}\right) - \pi_T^{n\cdot\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pC}}} - \left(k_{IC} \cdot \pi_T^{(1-n)}\right)^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pC}}} + 2}{\frac{\theta - \left(k_{IC} \cdot \pi_T^{(1-n)}\right)^{\frac{\kappa-1}{\kappa}\cdot\frac{1}{\eta_{pC}}}}{1 - \theta \cdot \frac{c_p T_0}{H_U}}}. \tag{3.22.}$$

3.3 Results

In the previous chapters the equations describing the intercooled cycle were derived. This subchapter presents the quantitative representation of those formulae.

The choice of the representation of the parameters was carefully made to present the results in a possibly clear way.
For all the calculations some parameters had to be fixed:

$$H_U = 50\frac{MJ}{kg}.$$

In the case when the efficiencies are included following values are used:

$$\eta_{pT} = 94\% \qquad \eta_{pLPC} = \eta_{pHPC} = \eta_{pC} = 92\%$$

$$k_{IC} = \frac{1}{0{,}9} = 1{,}11 \qquad k_{CC} = \frac{1}{0{,}89} = 1{,}12$$

The graphs have been presented in dependence on compression ratios of the compressors, expander and the turbine inlet temperature, represented by the parameter θ. The results represent $\frac{\omega}{c_p T_0}$ and η_{th} according to the formulae (3.10) and (3.13) for the ideal case and (3.19) and (3.22) for the case where thermodynamic losses are included. For each value graphs for three different θ parameters (4,00; 5,00 and 5,47 - the last one supposedly representing the LMS100) are presented.

3.3.1 Results for the case without losses

It may seem that there are only 6 plots on the graphs representing the dimensionless specific work, in fact the remaining 5 are overlapped in accordance to the formula (3.9). In these figures the maximum can be observed only in figure 10 and figure 11 for the extreme values of n. It can be noticed that it increases with the increase of T_4. Additionally for the higher values of θ it also moves to the regions of higher expander pressure ratio.

The pressure ratios reach their peaks always for the n=0.5, which was expected.

The plots representing efficiency have no maximum. They tend to reach 100%, which is a result of not including losses in the calculations. The values of the thermal efficiency are the highest for n=0, when the low-pressure compressor is bypassed, which denotes a simple cycle. Then for increasing n the thermal efficiencies are decreasing. Interesting is the fact that with the growth of the parameter θ the efficiencies for n=0 are decreasing and those for n=1 are increasing.

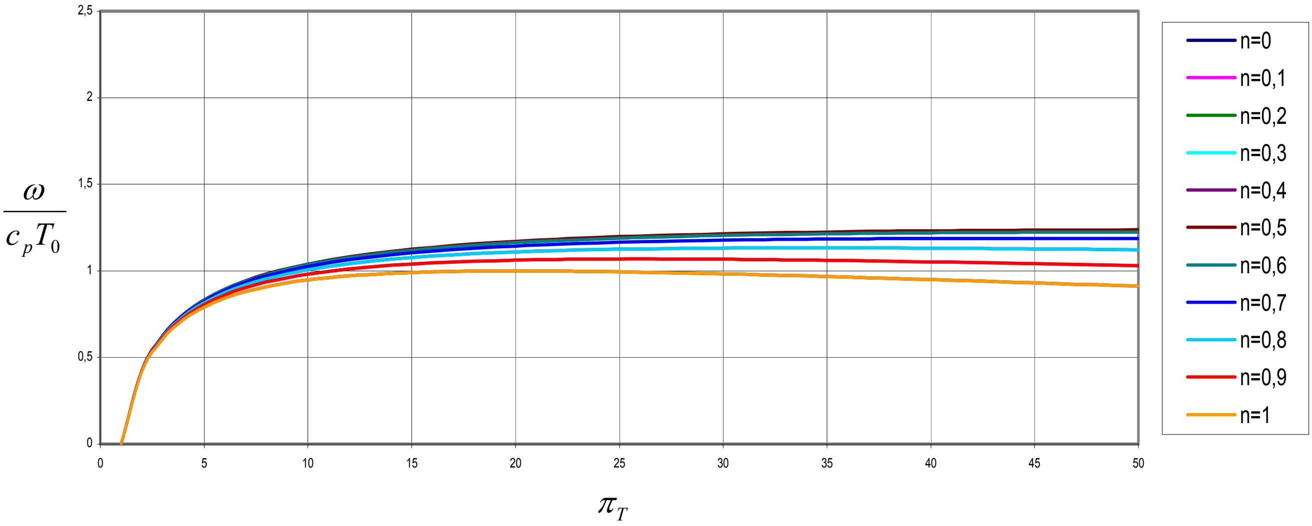


Figure 10: Dimensionless specific work (π_T, n, θ=4.00, k_{cc}=1, k_{ic}=1, η_{pt}=1, η_{pc}=1)

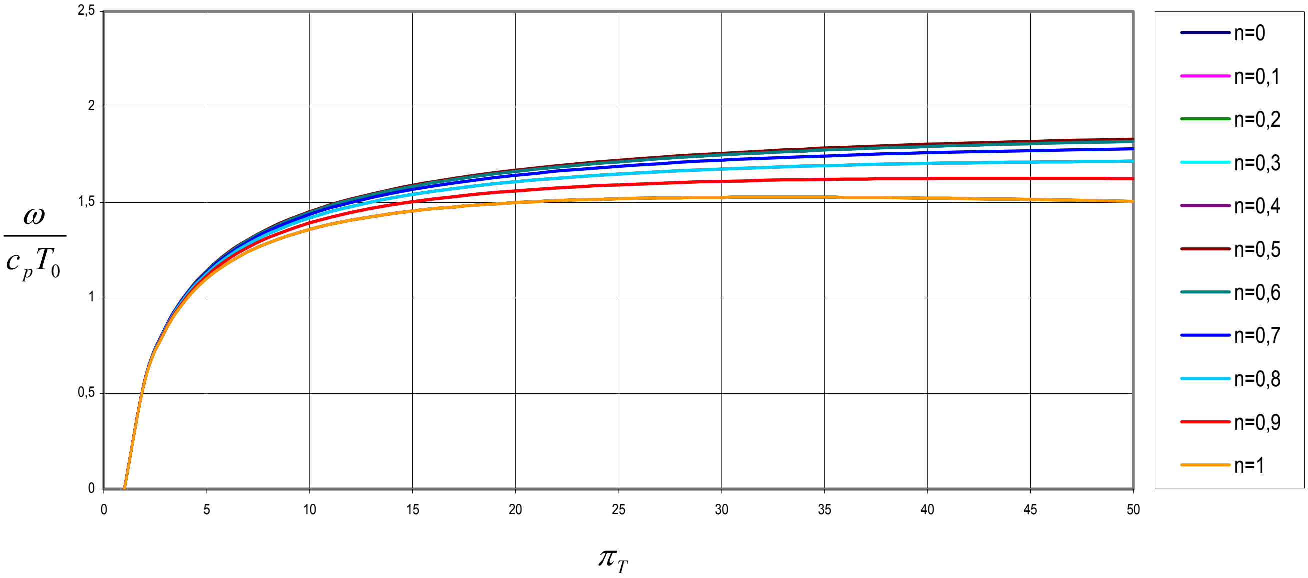


Figure 11: Dimensionless specific work (π_T, n, θ=5.00, k_{cc}=1, k_{ic}=1, η_{pt}=1, η_{pc}=1)

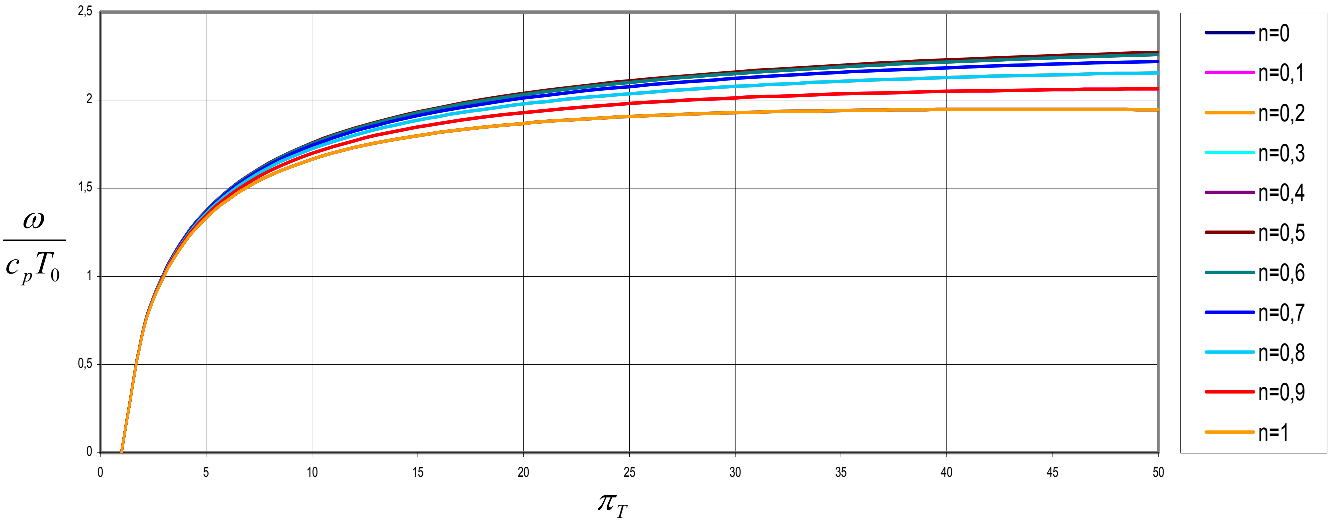


Figure 12: Dimensionless specific work (π_T, n, θ=5.74, k_{cc}=1, k_{ic}=1, η_{pt}=1, η_{pc}=1)

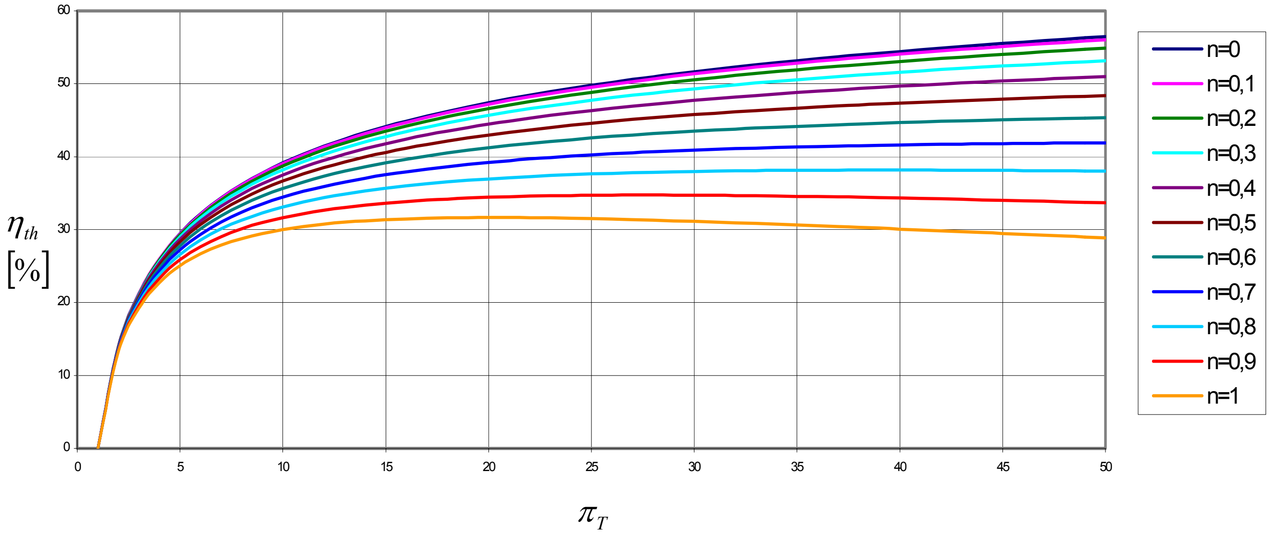


Figure 13: Thermal efficiency (π_T, n, θ=4.00, k_{cc}=1, k_{ic}=1, η_{pt}=1, η_{pc}=1)

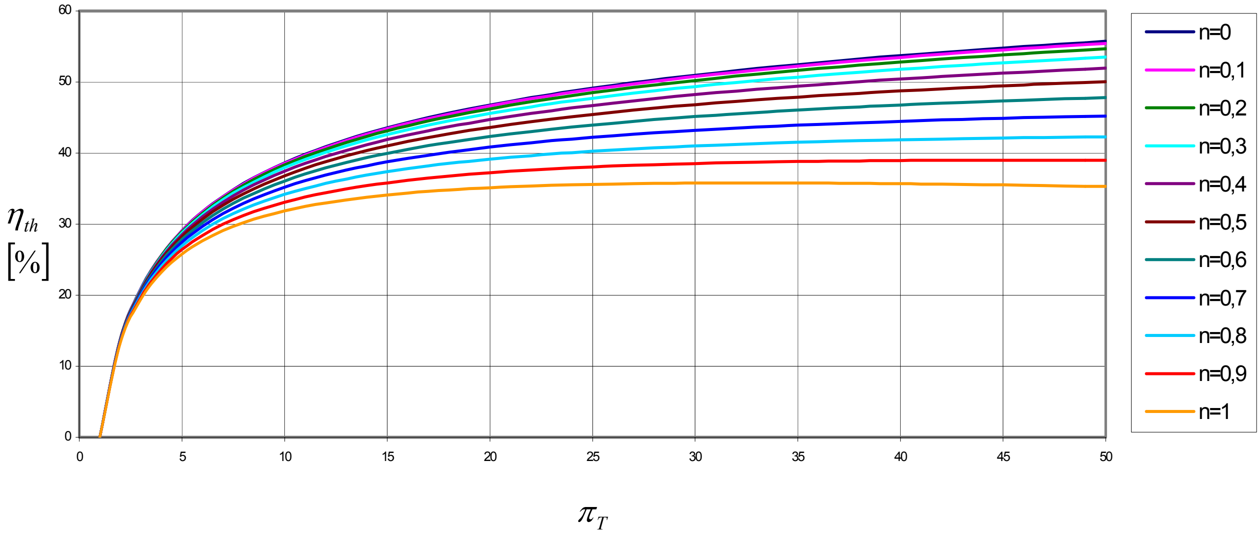


Figure 14: Thermal efficiency (π_T, n, θ=5.00, k_{cc}=1, k_{ic}=1, η_{pt}=1, η_{pc}=1)

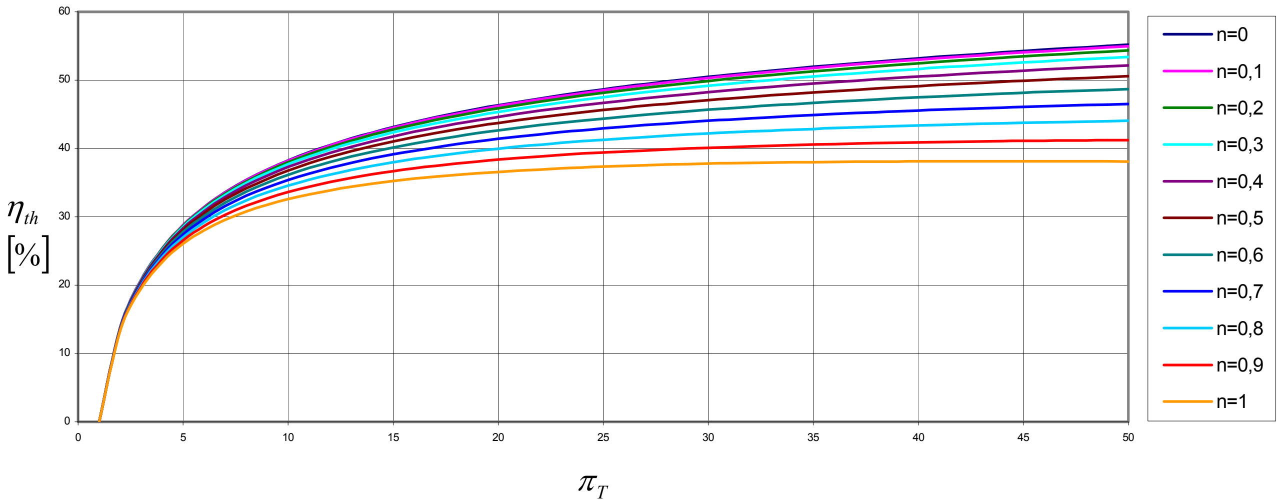


Figure 15: Thermal efficiency (π_T, n, θ=5.74, k_{cc}=1, k_{ic}=1, η_{pt}=1, η_{pc}=1)

3.3.2 Results for the case with losses included

The behavior of the dimensionless specific work is similar to the previous case. The peak also occurs for n=0,5 meaning that the pressure ratios of the compressors are equal. However, in general here the values are significantly smaller by about 25%. The second observed difference is that the peaks occur for finite values of π_T. The plots do not overlap anymore what results from formula 3.18, but the regularity that for the constant turbine pressure ratio values of $\omega / c_p T_0$ grow with an increasing *n*, to decrease after they have reached the maximum for n=0,5 is kept.

The behavior of the thermal efficiency curves is the point of the investigation here.
The losses, taken into account, include the coefficient k_{IC} which results in the general decrease of the value of thermal efficiencies by about 5%.
For each considered *n* a maximum of thermal efficiency occurs. The general trend is that the value of the maximum grows with the increase of θ. It happens then for the higher values of π_T. For small values of π_{LPC} from 1 to 2,5 the situation is different. The value of the maximum grows with the growth of π_{LPC}. The maximum η_{th} reached at $\pi_{LPC} = 2{,}5$ is the highest value reached for the investigated θ. This interesting phenomenon could have been used in design of the LMS100, if the thermal efficiency was a crucial factor.

In comparison to the ideal case no significant changes can be observed in the range of small cycle compression ratios. It can be concluded that for this region intercooling seems to be not giving any advantages, which is expected after [3].

The optimal compression ratios for the highest efficiency and highest dimensionless specific work are not corresponding with each other, which is consistent with [12].

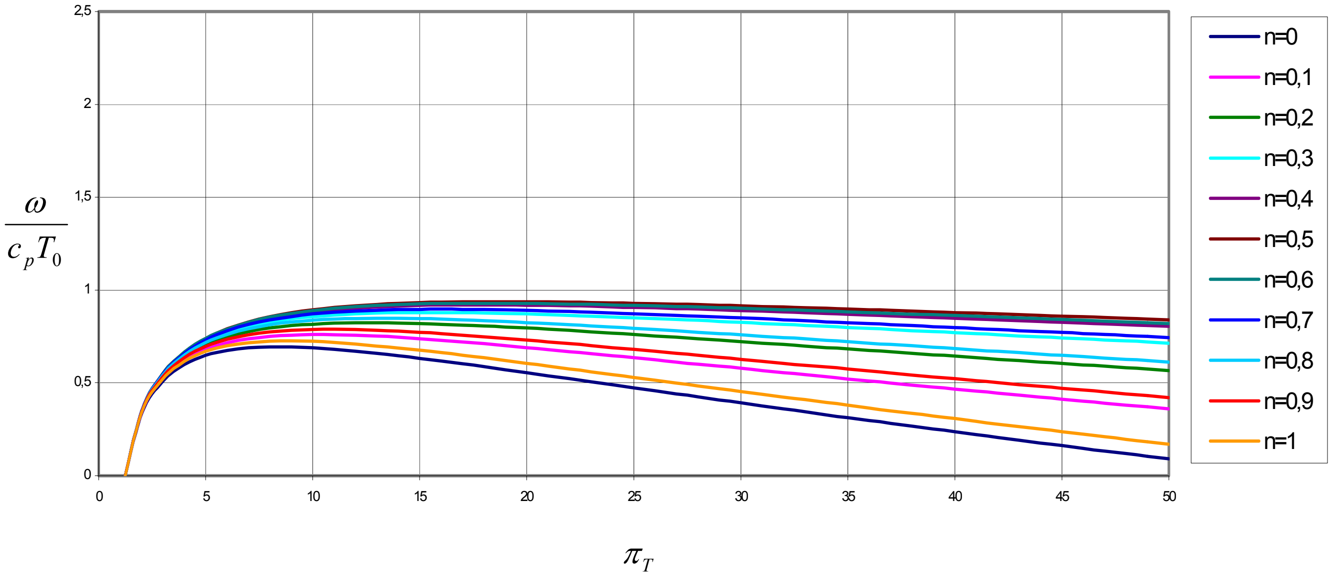


Figure 16: Dimensionless specific work (π_T, n, θ=4.0, k_{cc}=1.12, k_{ic}=1.11, η_{pt}=0.94, η_{pc}=0.92)

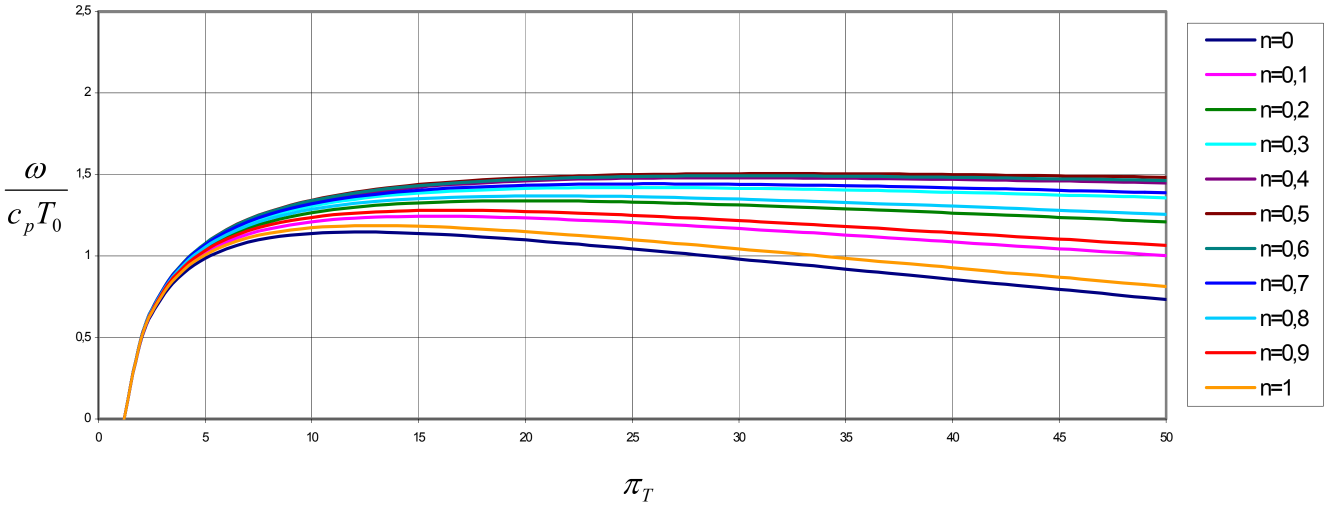


Figure 17: Dimensionless specific work (π_T, n, θ=5.0, k_{cc}=1.12, k_{ic}=1.11, η_{pt}=0.94, η_{pc}=0.92)

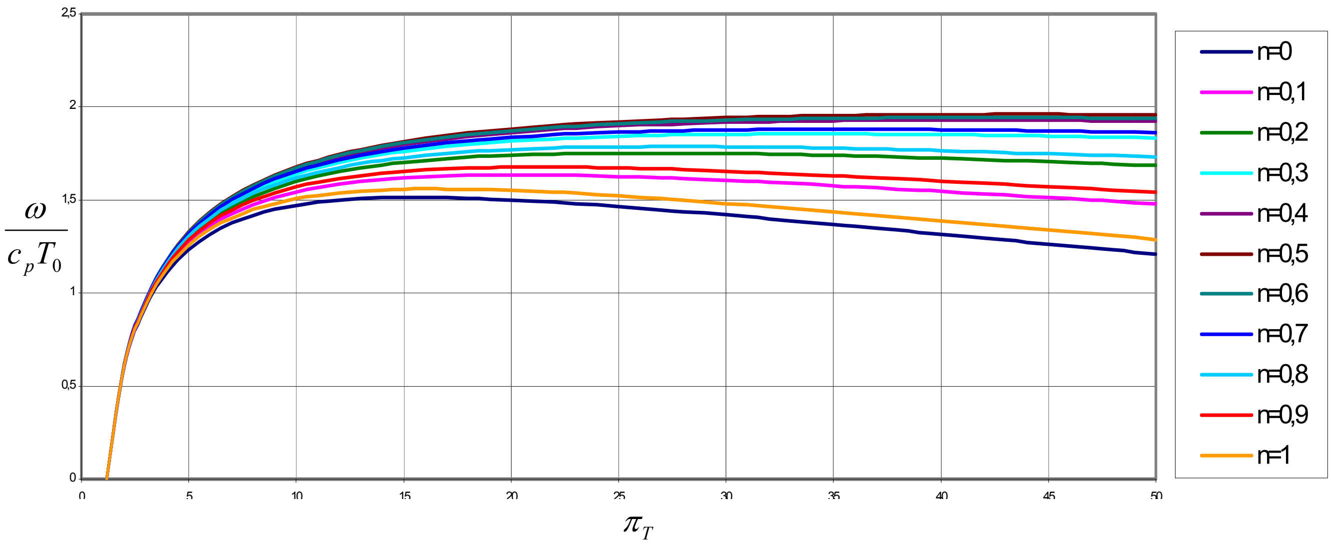


Figure 18: Dimensionless specific work (π_T, n, θ=5.74, k_{cc}=1.12, k_{ic}=1.11, η_{pt}=0.94, η_{pc}=0.92)

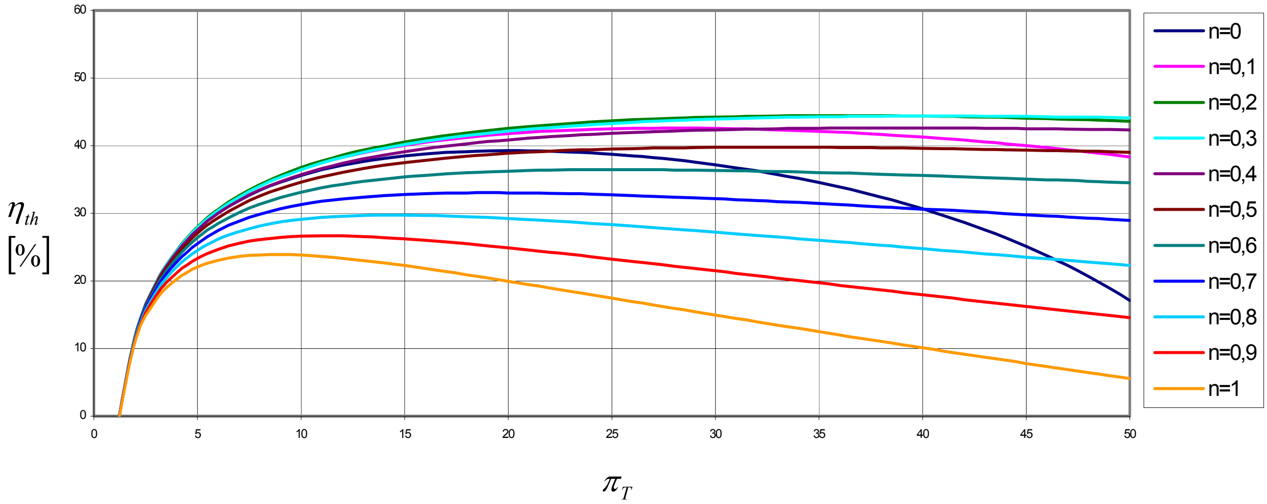


Figure 19: Thermal efficiency (π_T, n, θ=4.00, k_{cc}=1.12, k_{ic}=1.11, η_{pt}=0.94, η_{pc}=0.92)

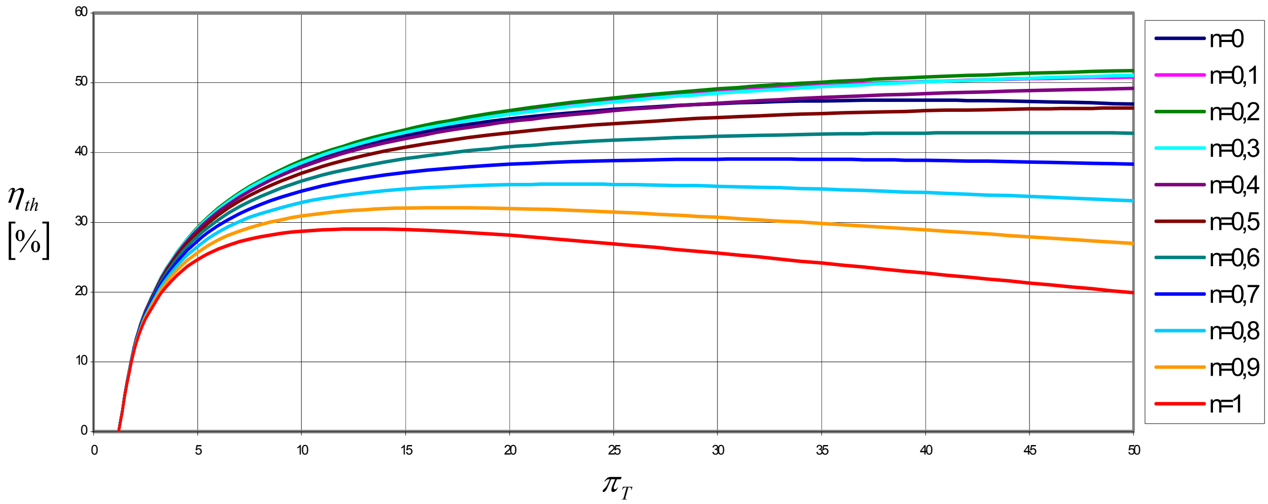


Figure 20: Thermal efficiency (π_T, n, θ=5.00, k_{cc}=1.12, k_{ic}=1.11, η_{pt}=0.94, η_{pc}=0.92)

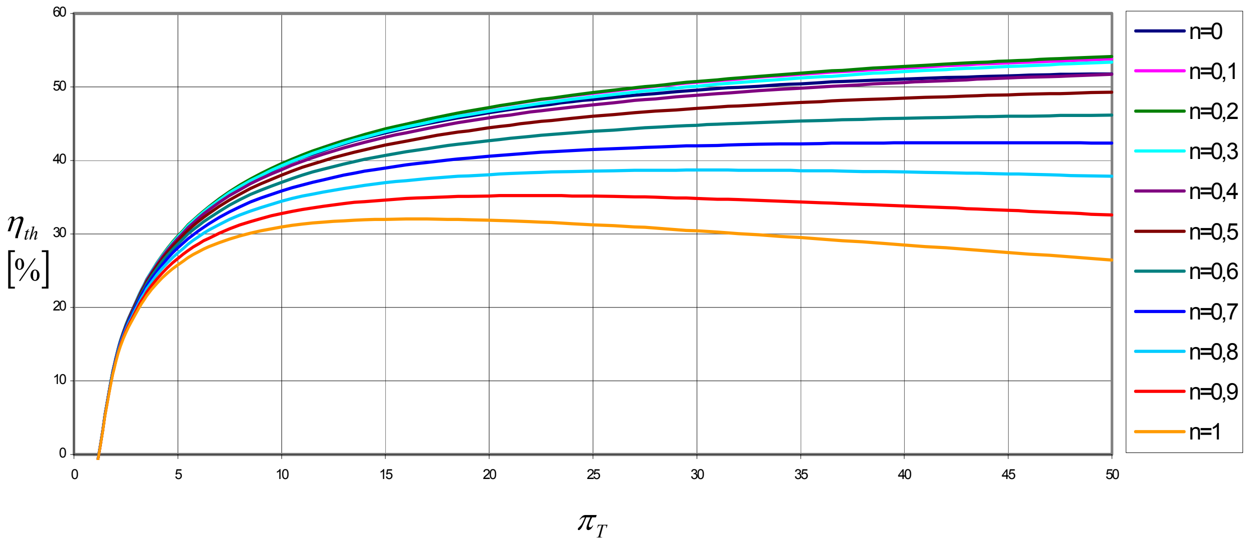


Figure 21: Thermal efficiency (π_T, n, θ=5.74, k_{cc}=1.12, k_{ic}=1.11, η_{pt}=0.94, η_{pc}=0.92)

4. Study of the thermodynamic cycle with GateCycle

This chapter describes the approach to the intercooled cycle with GateCycle. Firstly, short characteristic of GateCycle is presented, followed by the assumptions for the calculation in the program, description of the models used and in the end results and analysis.

4.1 Short characteristic of GateCycle and CycleLink

GateCycle is advertised to be the most flexible power-plant simulation software in the world. It predicts design and off-design performance of combined cycle plants, fossil boiler plants, cogeneration systems, combined heat-and-power plants, advanced gas turbine cycles and many other energy systems. GateCycle software is a powerful tool for both the gas and steam sides of power plant design and analysis. It has been under development since 1981 by GE Enter Software, which is fully owned by General Electric Power Systems. Used by over 500 users worldwide it is one of the most widely applied software for power plant design. Its component-by-component approach and advanced macro capabilities enable modelling of virtually any type of system.

GateCycle contains many features, which make it a powerful and flexible tool for modelling heat and power cycles with arbitrary complexity. A gas turbine can be selected from the library of gas turbines or “built” component-by-component and as a result intercooling, reheat, and even cascading gas turbines can be modelled. From the steam side, all the elements necessary to model HRSGs with multiple pressure levels, parallel sections and pressure losses are included. Also plant models with even several gas turbines and HRSGs with different configurations can be created. Additionally, macros in which the user can specify equations or define user functions allow controlling processes with more efficiency.

GateCycle gives also possibility to perform off-design simulations, which allows analyzing the performance of a “physically-based” component. However, this feature was not used during the work on this diploma thesis.

CycleLink, used during calculations, is a Microsoft Excel based utility, which allows full access to data within GateCycle. It allows customizing the output, performing further data analysis or preparing customized interfaces to the prepared models. At a higher level it allows to run case studies with GateCycle. Therefore, the data input on the Excel worksheets are written into a database of GateCycle. GateCycle gets readings from the database, solves the problem and writes the results to the database. The results get transferred into the Excel worksheets and can be used like any other data in Excel.

All the simulations were done in the program GateCycle for Windows Version 5.40.0r and elaborated by the means of CycleLink for Excel 97/2000 Version 3.3 produced by GE Enter Software LLC.

4.2 Assumptions for GateCycle simulations

Despite the marvellous possibilities of GateCycle it remains only a computer program with its limitations. That is why some assumptions were necessary before starting the calculations and so they will be described in this subchapter.

In principle the aim was to compare the results of the analytical calculations that has already been described in the previous chapter with the ones obtained in GateCycle for the same conditions. That means for both created models the following options in the program:

1. The ambient conditions are T_a=15°C and P_a=1bar.
2. The outlet pressure of the gas turbine's set to the ambient pressure.
3. LPC: specified pressure ratio, polytropic efficiency.
4. Intercooler: Hot side outlet temperature, pressure drop (k_{IC}).
5. HPC: no pressure control, polytropic efficiency.
6. Combustion Chamber:
    a. Combustor exit temperature (θ)
    b. Pressure drop (k_{CC})
    c. Fuel type: natural gas (100% CH_4), lower heating value equal 50000kJ/kg.
7. The turbine (expander): specified pressure ratio, polytropic efficiency.

Additionally, the second model with nozzle cooling includes a splitter which divides the outlet flow of the HPC into two parts in the relation that 17.5% (36.58kg/s) is directed to the cooling of the turbine and the rest enters the combustion chamber and further the turbine main inlet.
During the calculations the user defined variables and macros were used to make the work more efficient.

4.3 GateCycle simulations

By means of GateCycle a model of the corresponding intercooled gas turbine was prepared and the simulations were performed. Additional simulations including a new parameter - ΔT_{IC} - were made. This simulation was performed with the assumption that the heat exchanger does not work as assumed in the analytical calculations – cooling the air to the ambient temperature – but cools it to the value higher than the ambient temperature ΔT_{IC}.
A second model, which includes nozzle cooling, was also built. All the simulations and its parameters are represented in the table below.

	GateCycle model	k_{CC}	k_{IC}	η_{pT} $[\%]$	η_{pC} $[\%]$	ΔT_{IC} $[°C]$
Simulation 1a	1	$\frac{1}{0{,}89}$	$\frac{1}{0{,}9}$	94	92	0
Simulation 1b	1	1	1	100	100	0
Simulation 1c	1	$\frac{1}{0{,}89}$	$\frac{1}{0{,}9}$	94	92	40
Simulation 2	2	$\frac{1}{0{,}89}$	$\frac{1}{0{,}9}$	94	92	0

Table 2: Parameters of the simulations

Simulation 1

Intercooled gas turbine – corresponding as much as possible to the analytical model. The following set of simulations was performed on this model with the help of CycleLink:

a. $k_{CC} = 1{,}12$, $k_{IC} = 1{,}11$, η_{pT}=94%, η_{pc}=92% - with losses included

b. $k_{CC} = 1$, $k_{IC} = 1$, $\eta_{pT} = 100\%$, $\eta_{pC} = 100\%$ - without losses

c. $k_{CC} = 1{,}12$, $k_{IC} = 1{,}11$, η_{pT}=94%, η_{pc}=92%, ΔT_{IC} - with losses included and additionally with ΔT_{IC} considered. This parameter, which is depicted in figure 22, was added to see how exactly the value of the temperature after the heat exchanger influences the thermal efficiency – NOTE: in all other cases $\Delta T_{IC} = 0$.

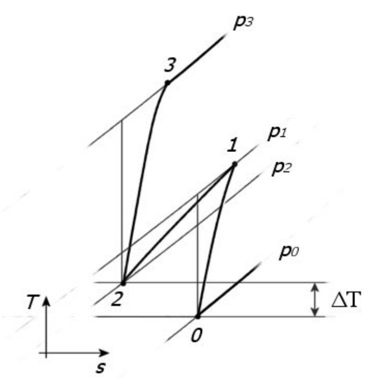


Figure 22: Depiction of ΔT_{IC}

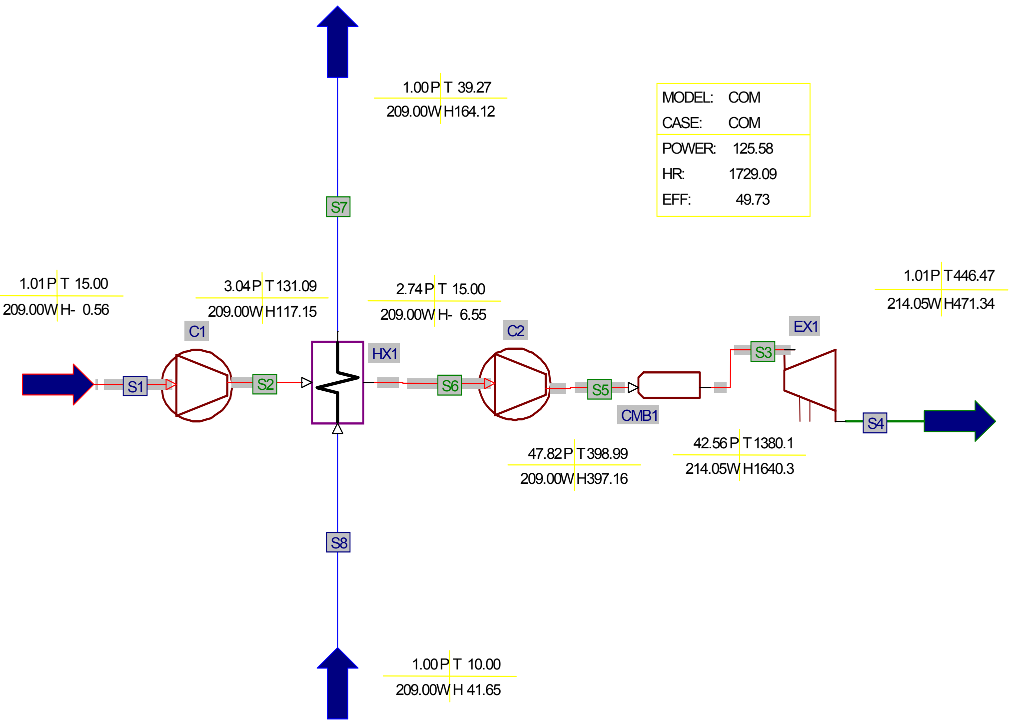


Figure 23: GateCycle model of the intercooled gas turbine

Simulation 2

Intercooled gas turbine with nozzle cooling introduces a parameter not included in the previous calculations, but having significant influence on the results, namely cooling of the turbine blades.

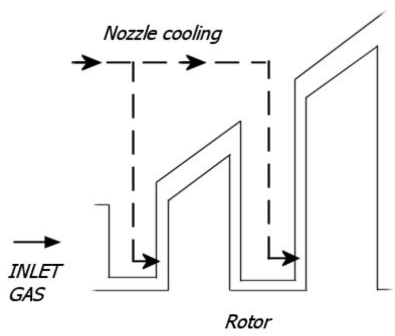


Figure 24: Nozzle cooling schema

The model of nozzle cooling uses specified cooling flow rate that is assumed to be 17,5% (36,58 kg/s) of the high-pressure compressor outlet flow. All the cooling flow is directed to the first stage, however there is a possibility to specify a cooling flow fraction going into each stage. A schema of nozzle cooling is depicted in figure 24.

For this model, depicted in figure 25, one set of simulations was performed ($k_{CC} = 1{,}12$, $k_{IC} = 1{,}11$, η_{pT}=94%, η_{pC}=92%).

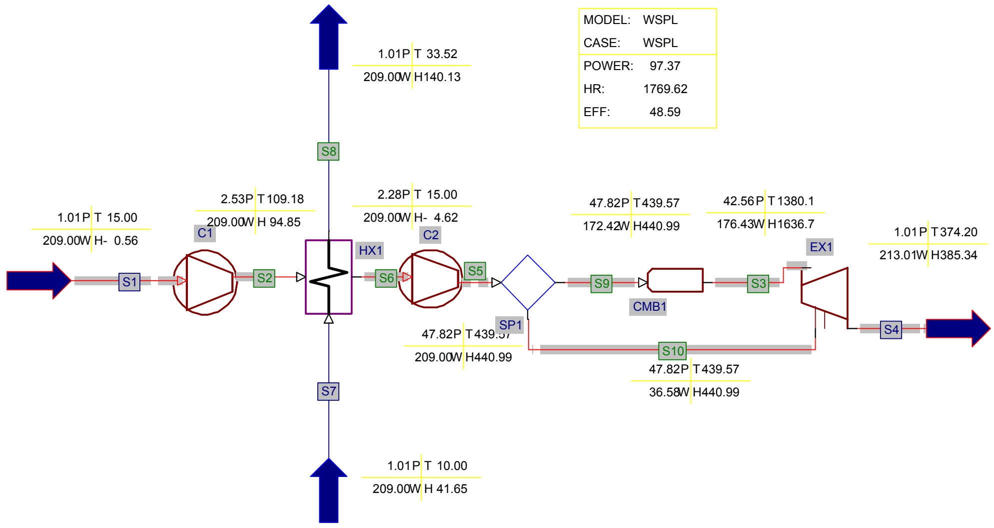


Figure 25: GateCycle model of the intercooled gas turbine with nozzle cooling included

In all these simulations the values of k_{CC} , k_{IC} ,, η_{pT} , η_{pC} are corresponding to the one used for the analytical calculations.

These 4 simulations were done in sets for changing parameter θ :

- $\theta = 4{,}00$ ($T_{TIT} = 880°C$)
- $\theta = 5{,}00$ ($T_{TIT} = 1170°C$)
- $\theta = 5{,}74$ ($T_{TIT} = 1380°C$).

The last one - $\theta = 5{,}74$ - is the LMS100 turbine inlet temperature.

4.2 Description and presentation of the simulations

GateCycle calculates many different values, however the focus of this diploma thesis has been put on a study of the thermal efficiency, as the most impressive feature of the LMS100 and so mainly this value will be investigated. Consequently, the dependences of mentioned above thermal efficiency on different configurations of pressure ratios and temperatures were researched.
The work with GateCycle would be much less efficient if not the help of CycleLink. After the models were created and saved, all the studies were done in Microsoft Excel.

The simulations were performed on the created models. The following variables were controlled during different series of simulations: desired polytrophic efficiency for LPC, HPC and turbine, combustion pressure drop, desired combustor exit temperature, heat exchanger hot side pressure loss. The value that was important, as an output was net cycle LHV efficiency, which is defined as the total power output divided by the total fuel consumption and expressed in percent.

4.3 Results

After performing the simulations, net cycle efficiency, which was the most significant of all results, were all sorted into sets and inserted into tables in Microsoft Excel, and then they were represented in the plots and analyzed. The result is presented in this subchapter.

Model 1a - with losses

This case is the basic one for this study. It implies all the same information that has been assumed for the analytical model.
Generally can be said that the results are similar however the values calculated with GateCycle seem to be round 5% smaller than in the analytical model. The reason for this decrease can be found in the heat capacity c_p assumed as constant for the analytical investigations.

For a constant parameter θ it can be observed that generally for a fixed π_T the value of η_{th} increases with the decreasing of π_{LPC}. An inverted trend can be observed for the small values of π_{LPC} from 1 to 2,5. The same type of phenomena occurred in the analytical model.

A maximum can be observed only for the condition when π_{LPC} has small values, for large values of π_{LPC} the maximum occurs for a turbine pressure ratio higher than considered 50.

By a closer examination of the graphs a surprising fact can be noticed that actually the case of $\pi_{LPC} = 1$, when the LPC and the heat exchanger are bypassed, gives better results than the intercooled model. A detailed study on the small range of π_{LPC} (1,3), represented on figure 26 shows that actually the maximal efficiency is reached not for π_{LPC} equal 1, but for the value around 2.

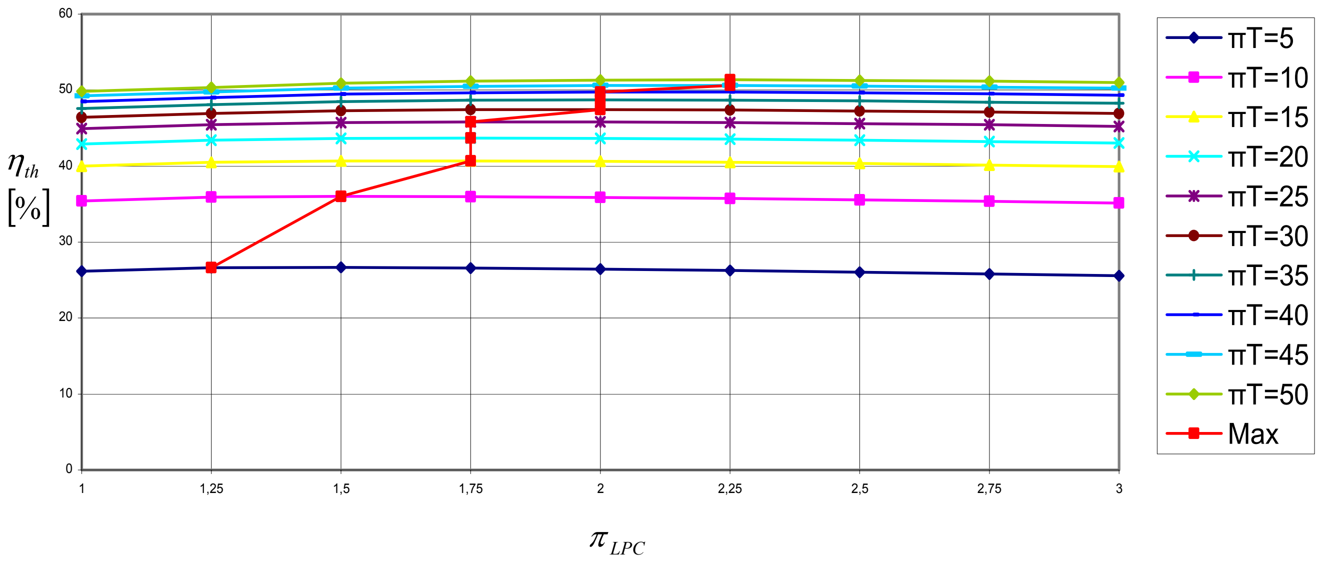


Figure 26: GateCycle Results of thermal efficiency

(π_{LPC}, π_T, θ=5.74, k_{cc}=1/0.89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%)

Analysis of all the plots with different θ parameter results in the observation that the thermal efficiency is growing with the increase of the turbine inlet temperature. Moreover, it can be said that it grows faster the high values of π_{LPC} than for the low ones.

The intercooling does not improve the cycle performance for a low cycle compression ratio, which is expected after [3].

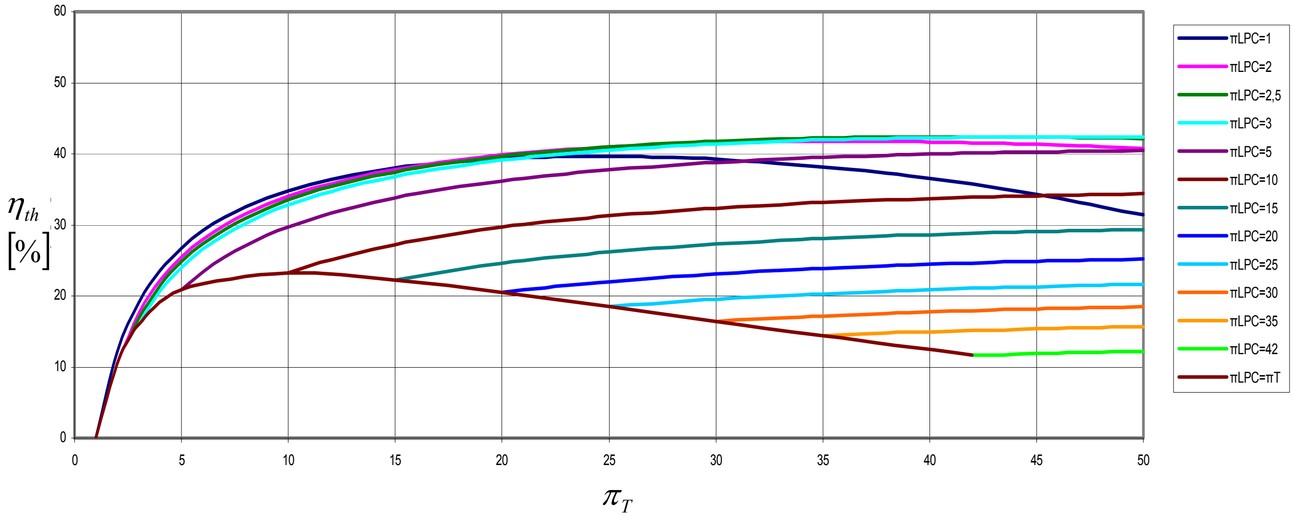


Figure 27: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=4.00, k_{cc}=1/0.89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%)

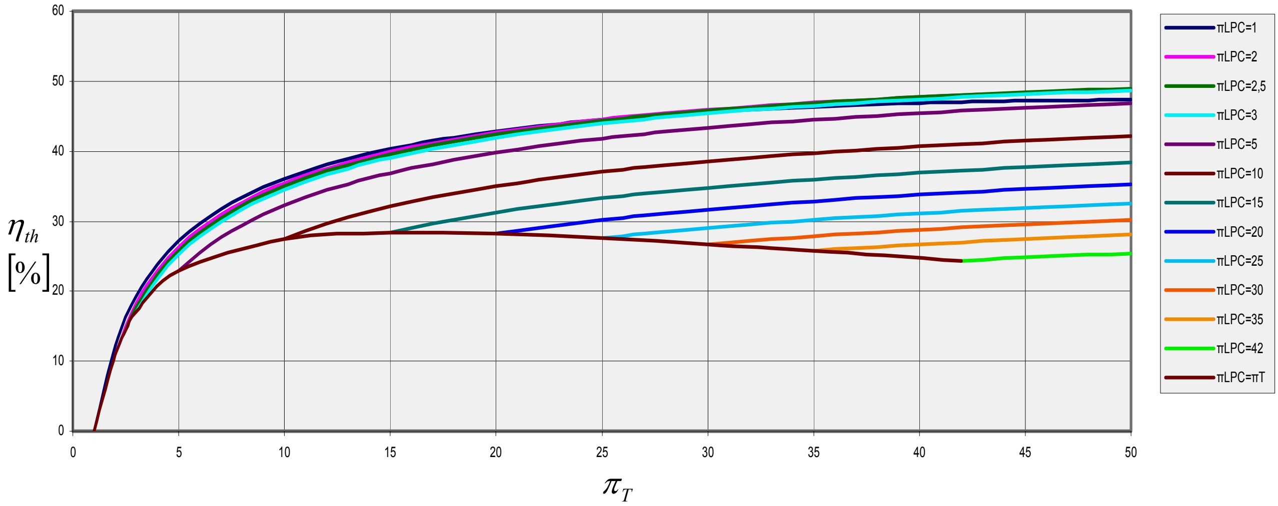


Figure 28: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=5.00, k_{cc}=1/0.89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%)

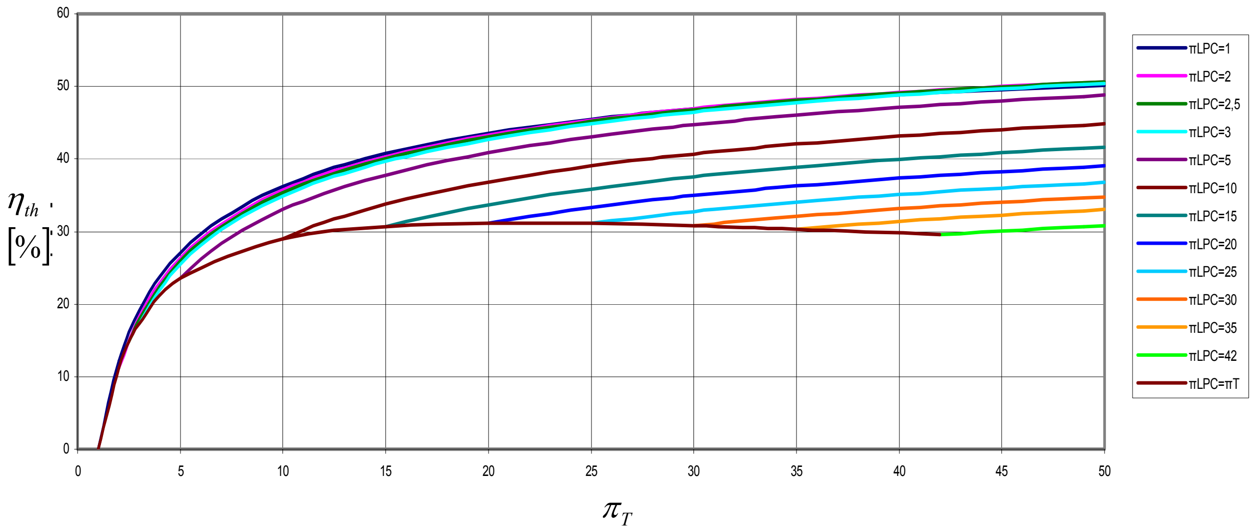


Figure 29: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=5.74, k_{cc}=1/0.89, kic=1/0.9, η_{pt}=94%, η_{pc}=92%)

Model 1b – no losses

The second simulation with the first model was made for the ideal case, which means that no losses were considered in the compressors, the heat exchanger, the combustion chamber and the expander.

In comparison to the model 1a the values of all the efficiencies are in this case round 10% higher, which is an obvious result of neglecting the losses. The graphs have no local maxima. Thermal efficiency is increasing for an increasing π_T, and decreasing π_{LPC} till it reaches 100%. On the contrary to the model 1a the biggest value of η_{th} happens for $\pi_{LPC} = 1$.

When the value θ increases, the highest efficiencies are slightly decreasing and the smallest increasing.

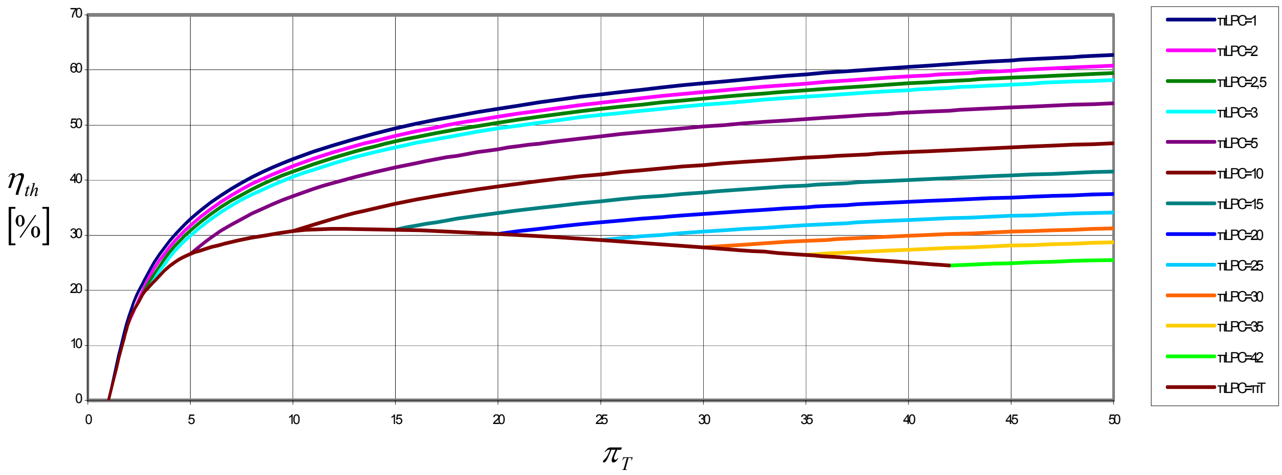


Figure 30: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=4, k_{cc}=1, k_{ic}=1, η_{pt}=100%, η_{pc}=100%)

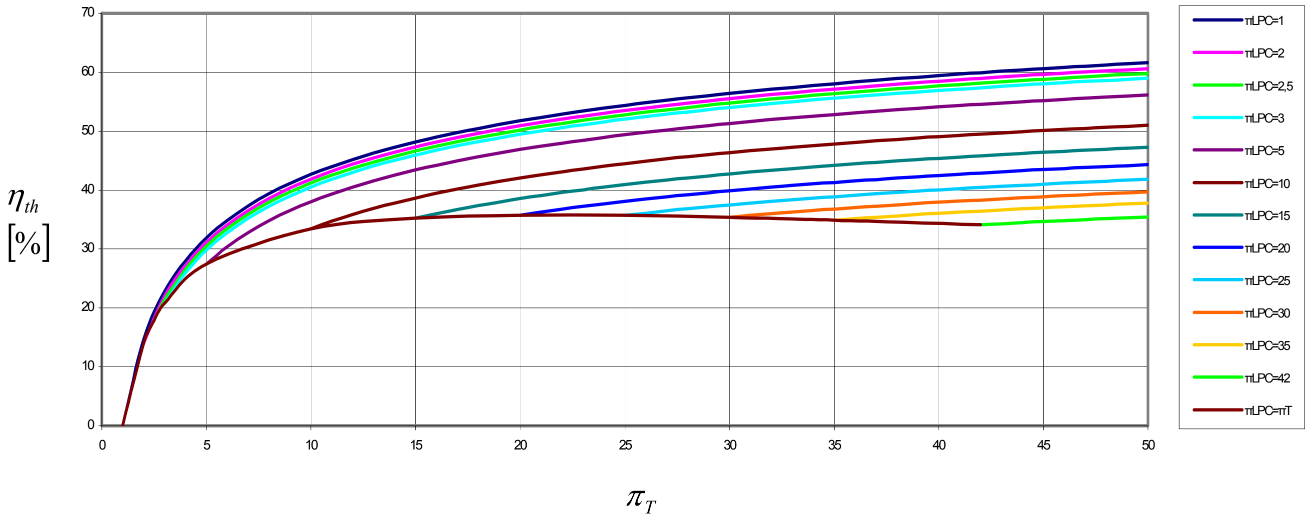


Figure 31: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=5, k_{cc}=1, k_{ic}=1, η_{pt}=100%, η_{pc}=100%)

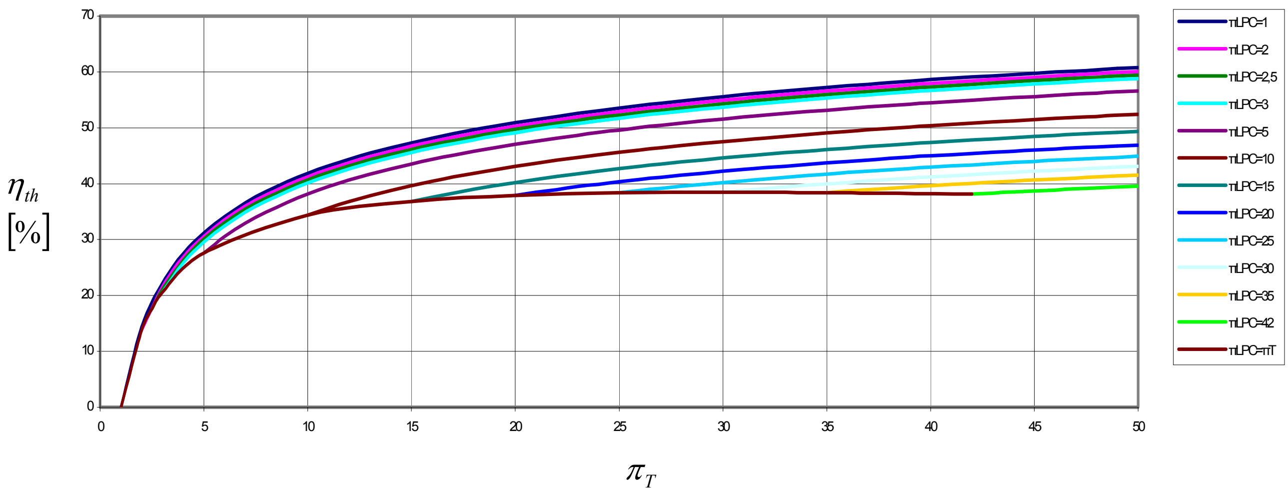


Figure 32: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=5.74, k_{cc}=1, k_{ic}=1, η_{pt}=100%, η_{pc}=100%)

Model 1c – higher than ambient temperature heat exchanger outlet temperature

Since the real conditions are unknown and the assumption made in the beginning that the heat exchanger cools the flow to the ambient temperature could be not true. It was sensible to check what happens in that case. The ΔT_{IC}=40K is an arbitrary value. The study is being conducted to show the behavior of the thermodynamic cycle under such a condition.

From the results, which are presented on figures 33-35, it can be concluded that the characteristics are similar as in the case of 1a. However, the efficiencies are smaller by 1 to 2%. The trend that the efficiencies are the highest for low values of π_{LPC} is kept.

It should be also noted that the plot for $\pi_{LPC} = 1$ is not there because as the LPC is bypassed the temperature of the flow is equal to the ambient so the heat exchanger would had to heat the flow instead of cooling it down which is not valid.

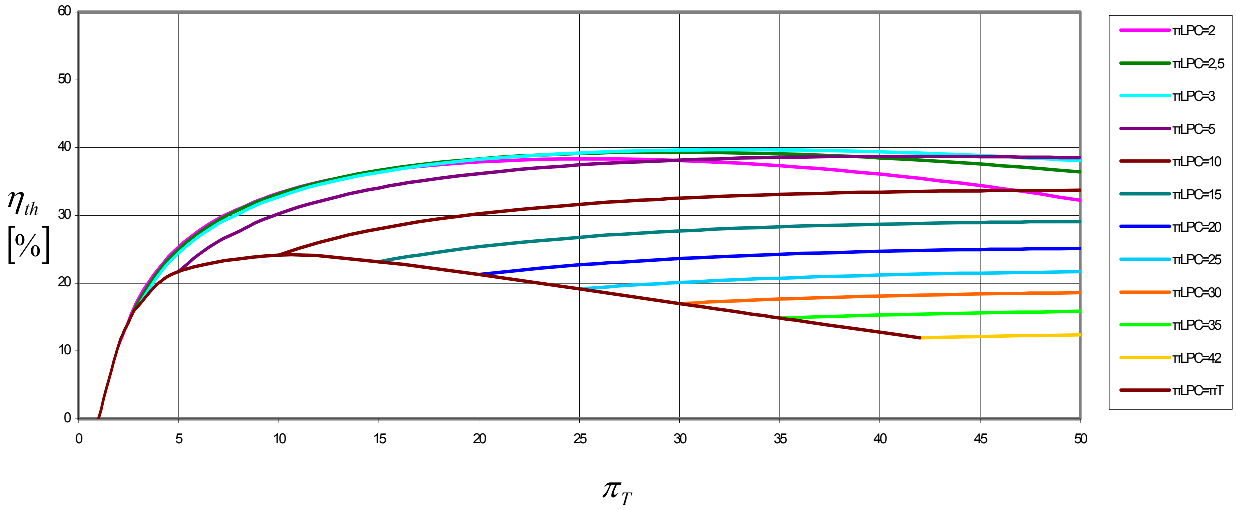


Figure 33: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=4, k_{cc}=1/89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%, dT=40K)

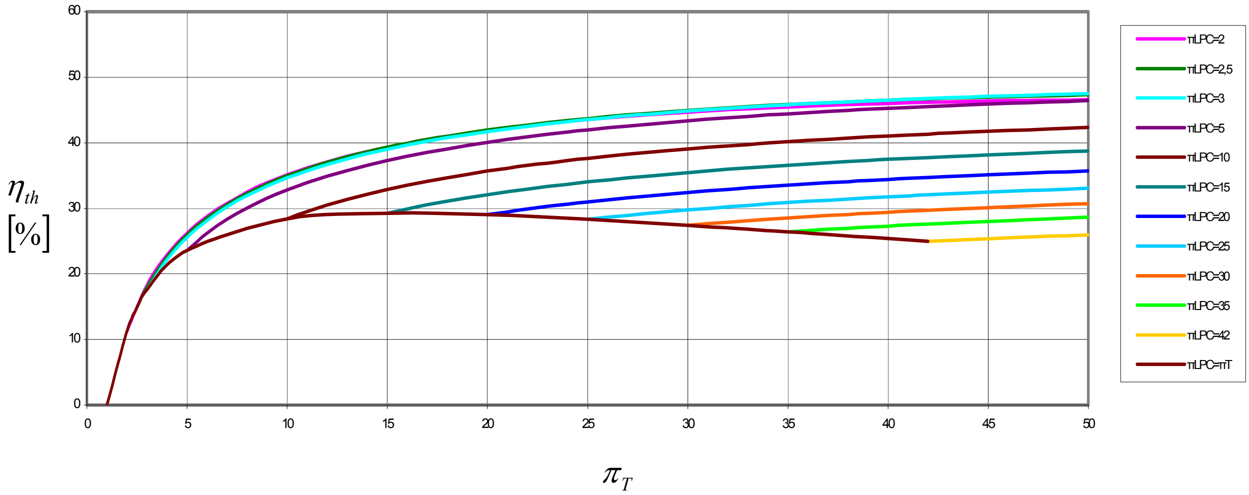


Figure 34: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=5, k_{cc}=1/89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%, dT=40K)

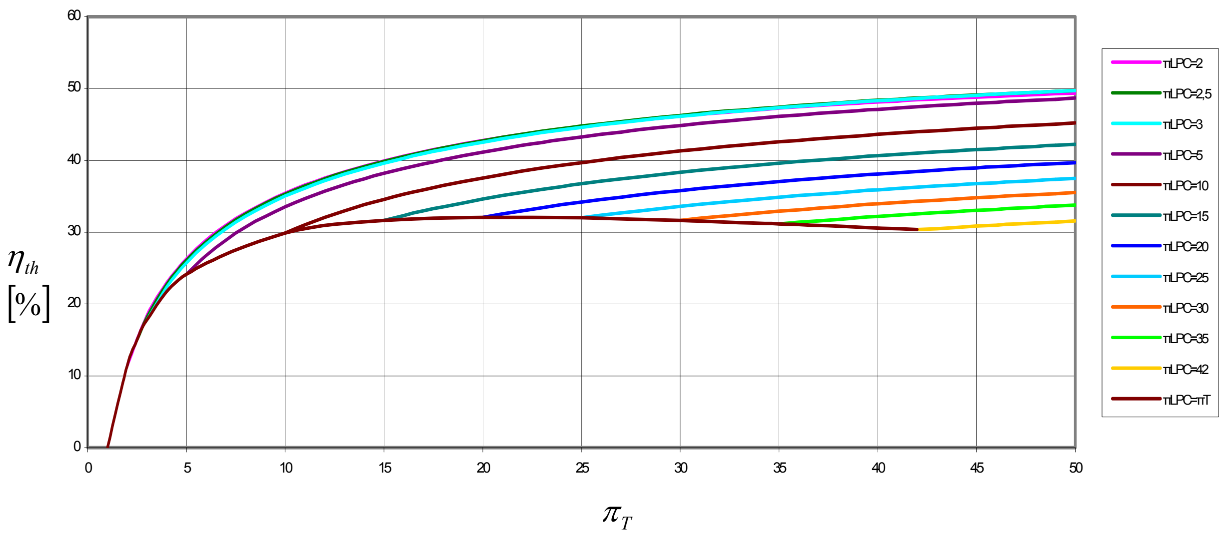


Figure 35: GateCycle Results – thermal efficiency (π_T, π_{LPC}, θ=5.74, k_{cc}=1/89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%, dT=40K)

Model 2 – nozzle cooling

These are the results for the second model made in GateCycle. This model seems to be the closest to the reality as the biggest amount of factors that influence the cycle is included. In comparison to 1a the thermal efficiency values are approximately 5% smaller. This is an expected response of the system to the inclusion of the nozzle cooling of the first stage.

Despite the decrease of η_{th} the overall trend, with the significantly high efficiencies for the small values of π_{LPC}, is kept.

However one must be aware that these are not all losses in this thermo dynamical cycle of the turbine, and that these results are not exact representation of the reality, but only show the phenomenon. The included parameters, which have been fixed, are only those that exert the biggest influence on the cycle, whereas the others are neglected. For these reasons this results should not be directly compared with the data concerning LMS100 availed by GE.

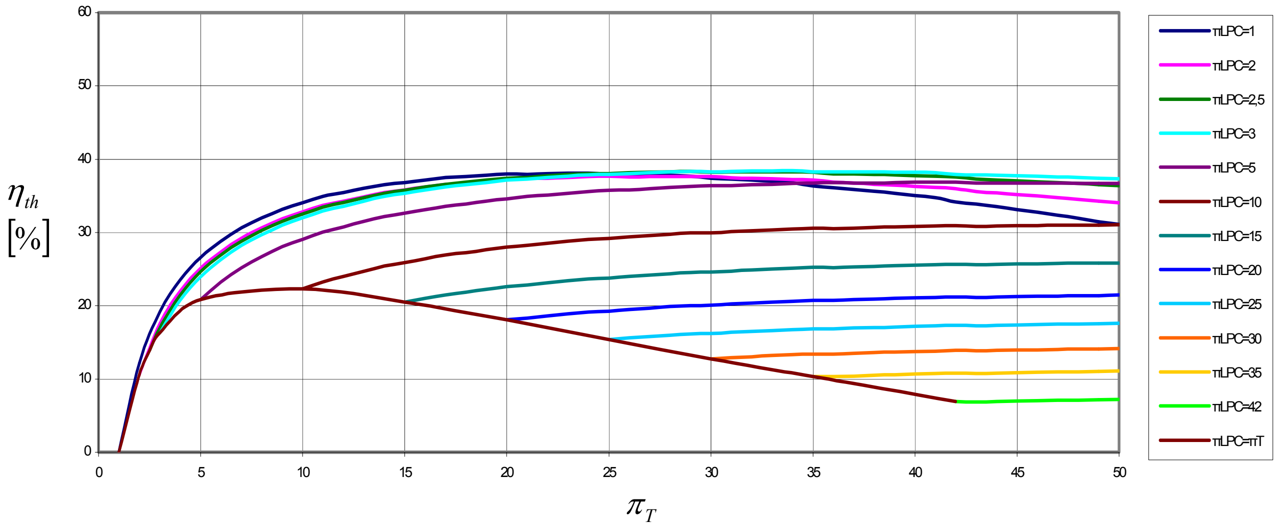


Figure 36: GateCycle Results (With nozzle cooling) – thermal efficiency (π_T, π_{LPC}, θ=4, k_{cc}=1/0.89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%)

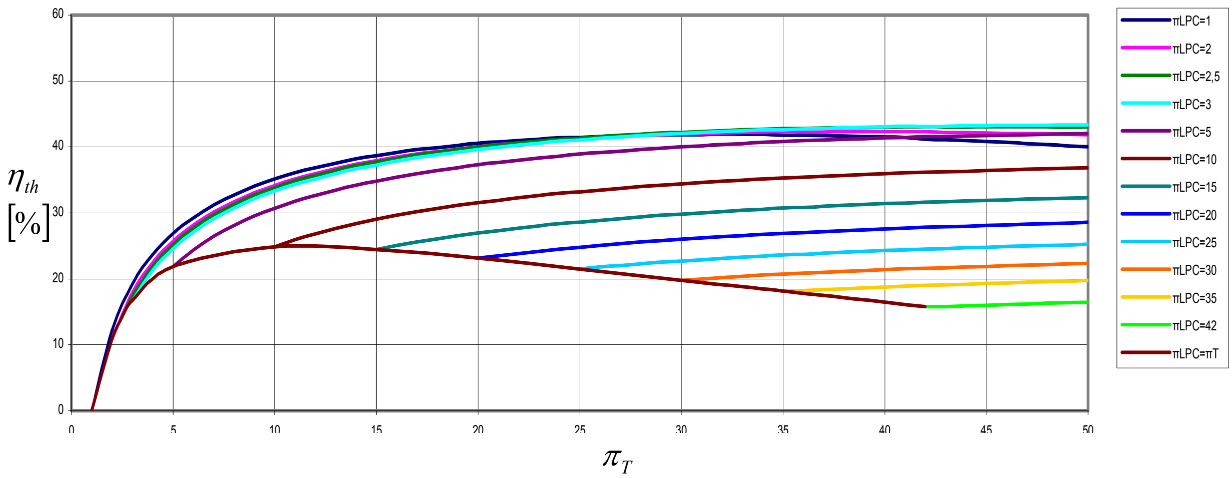


Figure37: GateCycle Results (With nozzle cooling) – thermal efficiency (π_T, π_{LPC}, θ=5, k_{cc}=1/0.89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%)

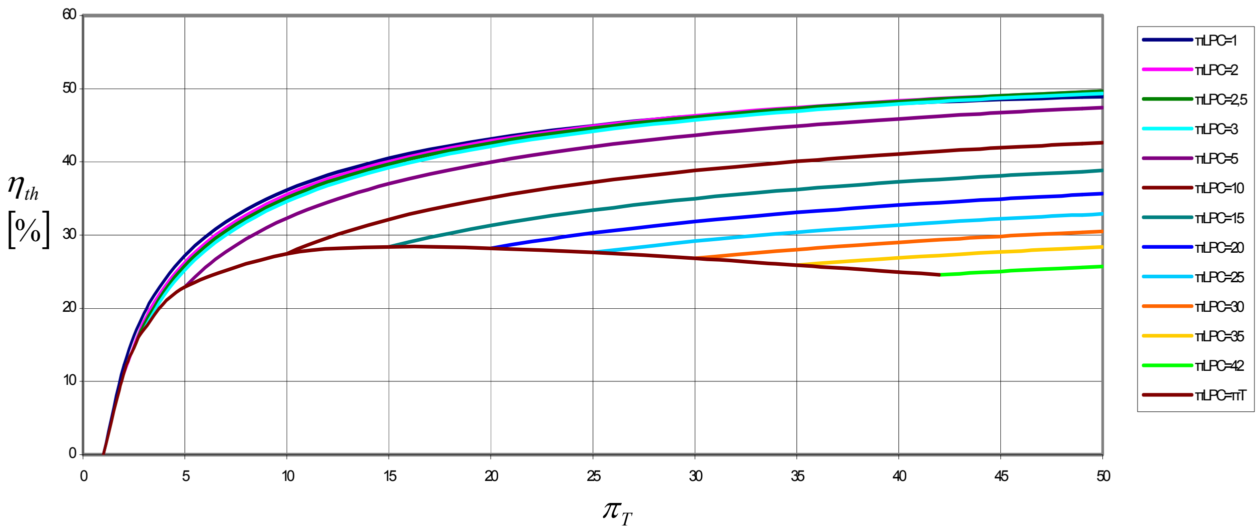


Figure 38: GateCycle Results (With nozzle cooling) – thermal efficiency (π_T, π_{LPC}, θ=5.74, k_{cc}=1/0.89, k_{ic}=1/0.9, η_{pt}=94%, η_{pc}=92%)

5 Conclusions

The thermodynamic study on the concept of intercooled compression process performed in this diploma thesis resulted in interesting results.

Two different methods, which were used, gave comparable results revealing a remarkable phenomenon occurring in the intercooled cycle. The investigation indicated that for high π_T and low values of π_{LPC} in the range of 1,5 to 3, the highest thermal efficiency is achieved. The fact that this knowledge was probably not used in technical applications before can be resulting from the property that the best results are achieved only for the very high values of cycle compression ratios. These were not achievable until recently when the heavy-duty frame gas turbine and aeroderivative gas turbine technology were effectively combined.

Additional investigations by means of Gate Cycle on the intercooled cycle showed that the introduction of another losses or turbine blades cooling decreases the value of the thermal efficiency, yet does not change the trend, which remains beneficial for the high values of π_T.

Furthermore, the study proved that the increase of the turbine-inlet temperature increases the thermal efficiency.

After performing of the analysis in this thesis it can be stated that an effective intercooled turbo system should have a high total pressure ratio and comprise of low-pressure compressor with a small pressure ratio round 2 and a high-pressure compressor, which compression ratio approximately 15-20.

Conclusions for the LMS100 design are not exact as simulation of precisely its cycle was unable because of lack of data. That is why all values achieved in the calculations contain a margin of error and should not be directly compared with the parameters provided by GE.

It cannot be ascertained, which parameters were given priority while designing the LMS100. It could have been high thermal efficiency, high specific work, combination of these two or another factor like for instance dimensions or reliability. However, the property of the intercooled cycle discovered in this work is highly probable to have been taken into account.

For each θ a precise value of turbine and compressors compression ratios when the system reaches its maximal efficiency is assigned. These parameters play a crucial role in the design process of the turbo engine, as they are the base point for searching for the optimal solution.

In the end it can be said that the LMS100 has a potential to “change the game in power generation” with its 46% of thermal efficiency. The future will show if the application of intercooled cycle, which seems to be perfect for high compression ratio cycles will find its place in the power generation industry.

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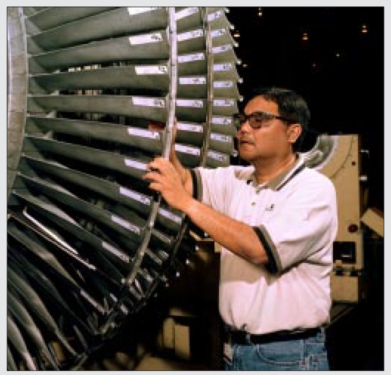

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The Tradition of Excellence Continues …

GE's New Gas Turbine System: Designed to Change the Game in Power Generation

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Only **GE** has the Imagination and Ability to Combine the… **Best of Both Worlds.**

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A New Beginning

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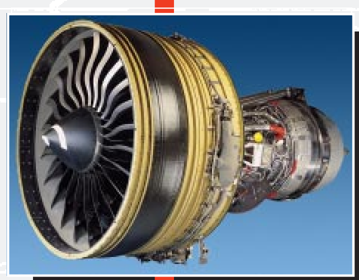
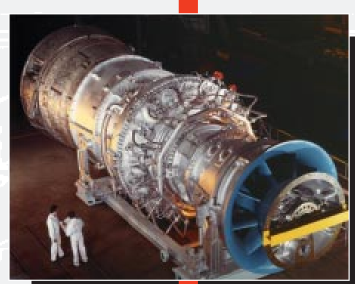




LM → LMS ← *MS*

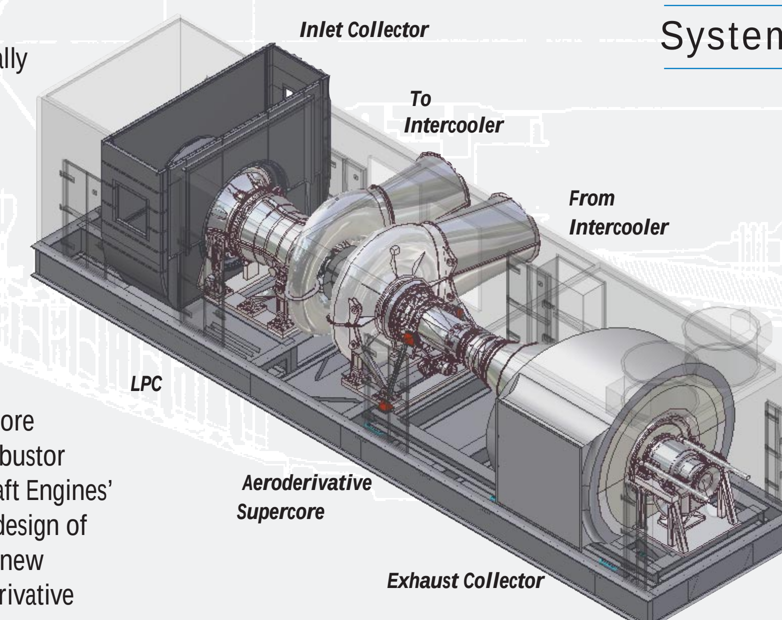
New High Efficiency Gas Turbine
For the Power Generation Industry

GE's New Gas Turbine Power Generation System

The **LMS100**™ is the first intercooled gas turbine system developed especially for the power generation industry, utilizing the best of two technologies -- heavy-duty frame gas turbine and aeroderivative gas turbine technology. The **LMS100** will deliver 100MW at 46% thermal efficiency. This efficiency is 10 % higher than GE's highest simple cycle efficiency gas turbine available today. It is specifically designed for cyclic applications providing flexible power for peaking, mid-range and baseload.

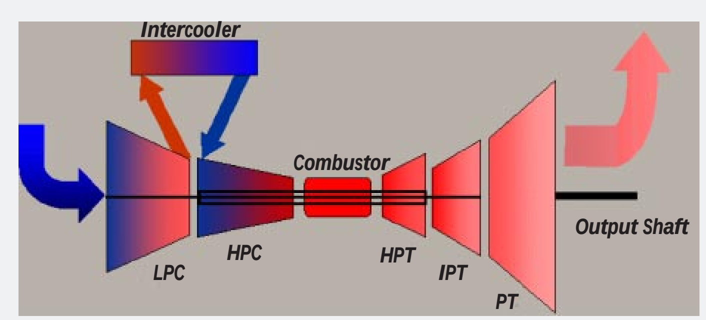
Flexible Power: High Efficiency

High Part-Power Efficiency, 50% Power	39%
High Simple Cycle Efficiency	46%
High STIG Efficiency	50%
High Combined Cycle Efficiency	54%



Only GE Can Bring You the Best of Both Worlds

The **LMS100** features a heavy-duty low pressure compressor derived from GE Power Systems' MS6001FA heavy-duty gas turbine compressor; its core which includes the high pressure compressor, combustor and high pressure turbine is derived from GE Aircraft Engines' CF6-80C2® and CF6–80E1® aircraft engines. The design of the new 2-stage intermediate pressure turbine and new 5-stage power turbine is based on the latest aeroderivative gas turbine technology. The exhaust and aft shaft for hot-end drive are designed using heavy-duty gas turbine practices.



The compressed air from the Low Pressure Compressor (LPC) is cooled in either an air-to-air or air-to-water heat exchanger (intercooler) and ducted to the High Pressure Compressor (HPC). The cooled flow means less work for the HPC, increased overall efficiency and power output. The cooler LPC exit temperature air, used for turbine cooling, allows higher firing temperatures, resulting in increased power output and overall efficiency.

The Right Solution.

Rugged Design With Proven Components. LMS100

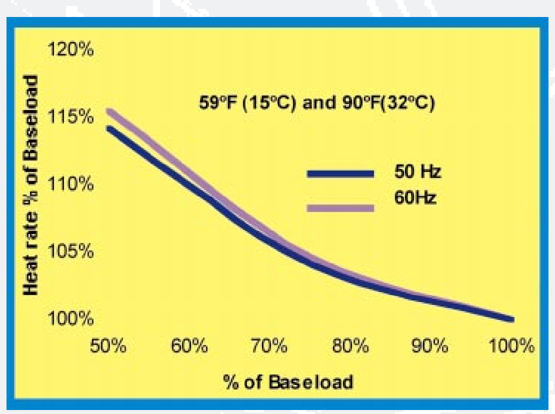
LMS100 Addressing Industry Needs

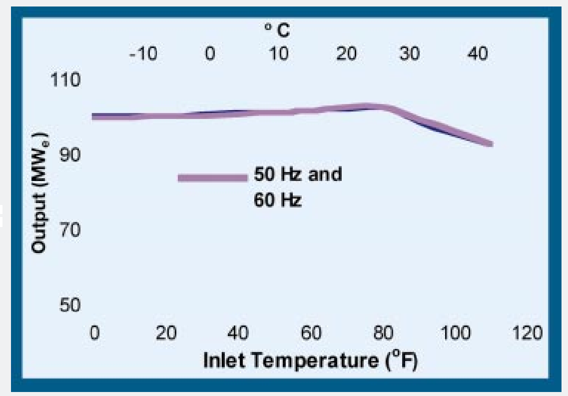
When asked to describe their requirements for future power generation facilities, customers identified the following items as high on their priority list:

- 100 MW blocks of power
- High efficiency at full and part-power
- Cycling capability
- Fast start
- Peaking capability
- Sustained hot-day power
- Fuel flexibility
- Low emissions

All agreed that a new gas turbine which met these requirements would be an important addition to their generation mix.

- The **LMS100** has been designed to specifically address all of these needs, changing the game in the power generating industry.





The LMS100 is the Right Solution:

- Outstanding full- and part-power efficiency
- Low hot-day lapse rate
- High availability — aero modular maintenance
- Low maintenance cost
- Designed for cycling applications
  - *No cost penalty for starts and stops*
  - *Load-following capability*
- 10 Minutes to full power
  - *Improves average efficiency in cycling*
  - *Potential for spinning reserve credits*
  - *Reduced start-up emissions*
- Synchronous condenser capability

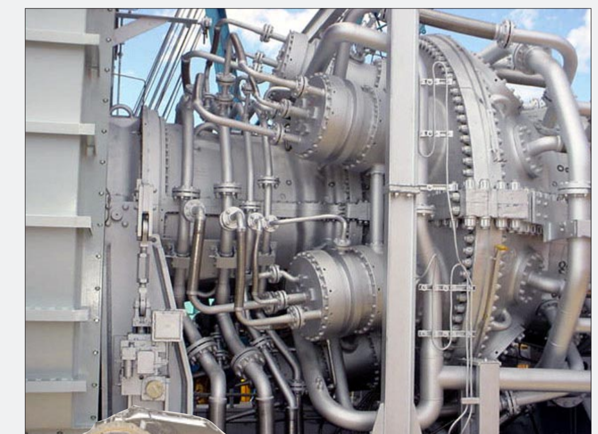
LMS100 Product Features

The **LMS100** features an inlet and an LPC comprised of the first six stages of the MS6001FA compressor. These stages are followed by an aerodynamically designed volute which ducts the low pressure compressed air into the intercooler. This LPC provides high airflow capacity for the **LMS100** Gas Turbine System.

Cooled air from the intercooler is ducted back through another aerodynamically designed volute into the aero supercore. The high efficiency aeroderivative supercore consists of:

- a high pressure compressor (HPC) based on the CF6-80C2 aircraft engine compressor, strengthened for the high (42:1) pressure ratio of the **LMS100**;
- a combustor which can be either a standard annular combustor (SAC) or an advanced dry low emissions (DLE2) combustor;
- a high pressure turbine (HPT) derived from the CF6-80E1 aircraft engine;
- a 2-stage intermediate pressure turbine (IPT) designed to drive the LPC through a mid-shaft and flexible coupling.

Following the IPT is a 5-stage aerodynamically coupled power turbine (PT) that has been designed specifically for the **LMS100**. The exhaust frame and aft drive shaft are based on a rugged heavy-duty gas turbine exhaust design.



Over 600 Advanced F Technology Units With Nearly 8 Million Fired Hours

3,786 CF6-80 Engines in Operation With More Than 103 Million Operating Hours

Industrial Example of a Finned Tube Heat Exchanger

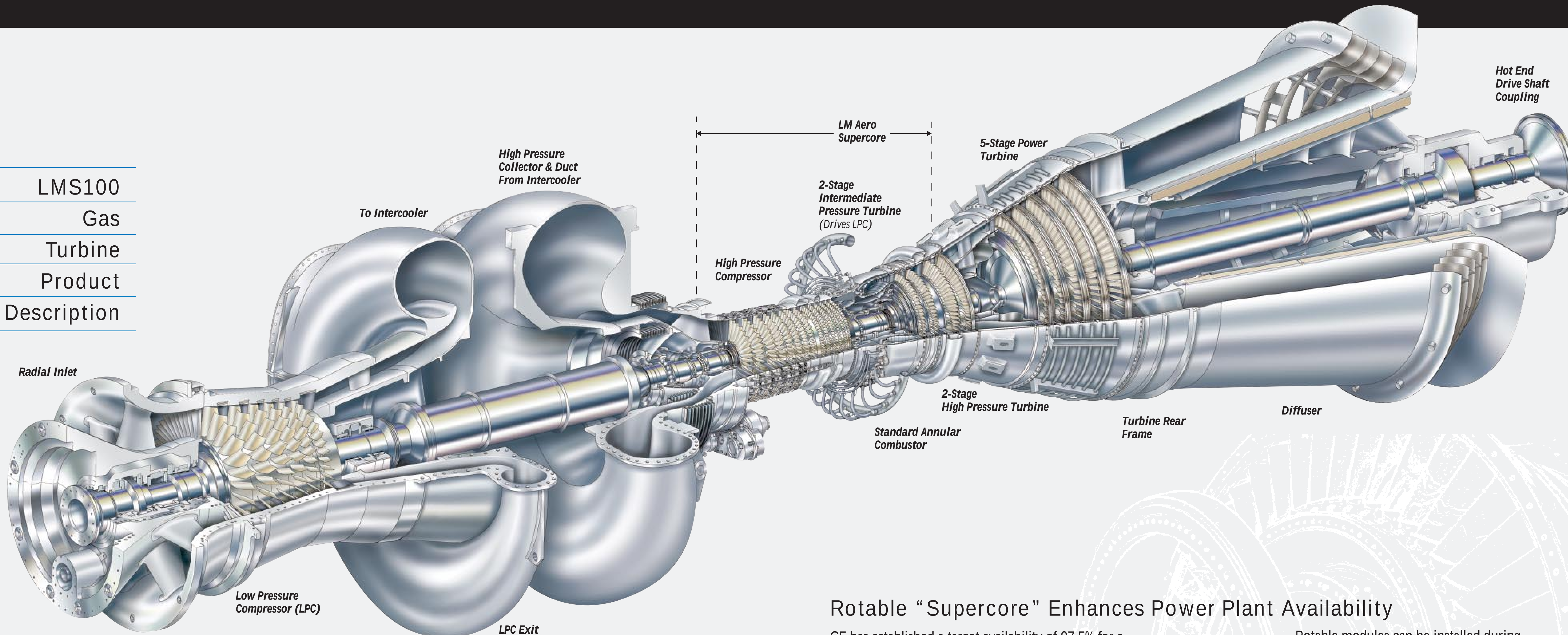
The LPC air is ducted to an air-to-air or air-to-water heat exchanger where it is cooled before being ducted to the HPC. Both designs are industry standard heat exchangers with significant operating hours in multiple industries and are designed to the API 660 and TEMA C standards.

Industrial Example of a Tube & Shell Heat Exchanger

Designed for Availability and Maintainability.

LMS100

LMS100
Gas
Turbine
Product
Description



Maintainability Features

- Modular construction permits replacement of the aero components without total disassembly.
- Multiple borescope ports allow on-condition monitoring without turbine disassembly.
- Condition based maintenance and remote diagnostics.
- Split casing construction of the LPC and aeroderivative compressor allows detailed on-site inspection and blade replacement.
- Hot-section field maintenance can be done in several days.
- Accessories are externally mounted for ease of on-site replacement.

Rotable "Supercore" Enhances Power Plant Availability

GE has established a target availability of 97.5% for a mature GE-built LMS100 power plant. Its power plant target reliability is 98.5%. The rotable "supercore" consists of the HPC, Combustor, HPT and IPT modules.

LMS100 Service Intervals

The expected service intervals for the LMS100 based upon normal operation include:

- On-site hot-section replacement.............................25,000 fired hours*
- Depot maintenance; overhaul of hot section and inspection of all systems, power turbine overhaul ...50,000 fired hours*
- Next on-site hot section replacement ....75,000 fired hours*
- Depot maintenance..100,000 fired hours*

*Note: These are actual fired hours; no multipliers for cycling are needed.

Rotable modules can be installed during on-site maintenance. A lease or spare "supercore" and a power turbine module can be installed in 24 hours when depot maintenance is required.

Maintenance Services

All warranty and follow-on services for the LMS100 will be provided by GE Power Systems on-site or at its several depot locations around the world. These services can include Contractual Service Agreements, Lease Engines, Spare Parts, Rotable Modules, Training and Training Tools.

Package Design

The **LMS100** gas turbine package system was designed for reliable operation, easy access for maintenance and quick installation. The auxiliary systems are pre-assembled on a single skid and factory tested prior to shipment. The auxiliary skid is mounted in front of the turbine base plate utilizing short flexible connectors reducing mechanical interconnects by 25%. The complete gas turbine driver package can be shipped by truck.

LMS100 Plant System Design

While the actual plant layout will be site dependent, it will contain basic elements which include an inlet, an auxiliaries skid containing a water wash system, lube oil system and starter system, a turbine skid, an intercooling system, a generator, silencers, exhaust system and a control system.

Control System

Significant emphasis has been placed on controls design for increased reliability of the entire power plant. The **LMS100** control system will have dual channel architecture with a cross-channel data link providing redundancy which will allow multiple failures without engine shutdown. A fiberoptic distributed I/O system located outside the module will be unaffected by electromagnetic or radio frequency interference which will eliminate noisy wiring. Site interconnects are reduced by 90% compared to the typical gas turbine control system.

Fuels

The **LMS100** SAC will be equipped with dual fuel capability so that it can burn either natural gas or distillate fuels. The **LMS100** DLE will operate on gas fuel.

Emissions Control

The **LMS100** gas turbine system has all the advantages of an aeroderivative gas turbine in achieving low emissions. The **LMS100** gas turbine with the SAC combustor (using water or steam for NOx control) and the advanced DLE combustor (DLE2) are designed to achieve 25 ppm NOx. This represents a 7 to 18% reduction in mass emissions rate (lbs/kwh) vs. the LM6000. In locations where less than 25 ppm NOx is required a low temperature SCR can be used. The high efficiency of the **LMS100** results in exhaust temperatures below 800ºF (427ºC) which permits the use of low temperature SCRs without tempering air.

Noise Control

The gas turbine-generator will be rated at 85 dBA average at 3 feet (1 meter). An option for 80 dBA at 3 feet will be available.

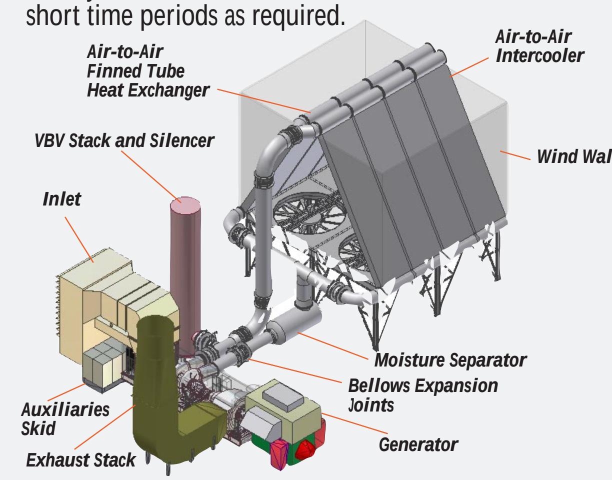
Generator

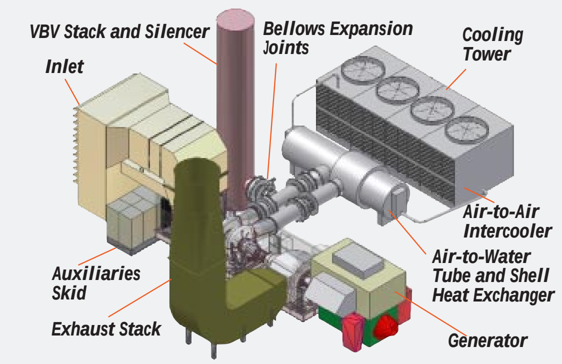
The generator is dual rated for 50 or 60 Hz applications. Either an air-cooled or TWAC configuration can be provided.

LMS100 Plant System Design

Air-to-Air Intercooler

In locations where water is scarce or very expensive, the basic **LMS100** power plant will contain a highly reliable air-to-air intercooler. This unit will be a tube and fin style heat exchanger in an A-frame configuration which is the same as typical steam condensing units in general conformance with API 661 standards. Similar units are in service in the Oil and Gas industry today. In high ambient temperature climates, an evaporative cooling system can be added for power augmentation. This system would use a small amount of water for short time periods as required.





Air-to-Water Intercooler

In locations where water is readily abundant or less expensive the intercooler can be of the air-to-water type also found in many industrial applications. The intercooler would be a tube and shell type heat exchanger.

Either type of intercooler will be connected through a system of piping and expansion bellows, from the low pressure compressor volute to the intercooler and upon return to the high pressure compressor inlet volute.

LMS100 is Available in a Variety of Configurations

Four basic LMS100 configurations are available as this product is introduced. When combined with intercooler selection and duty applications, the LMS100 will offer the customer 20 different configuration choices.

LMS100 SYSTEM CONFIGURATIONS

Product Offerings	Fuel	Combustor	Diluent	Power Augmentation	NOx Level
LMS100 SAC, 50/60 Hz	Gas, Liquid or Dual Fuel	Single Annular (SAC)	Water	None	25 ppm
LMS100 SAC Steam, 50/60 Hz	Gas	Single Annular (SAC)	Steam	None	25 ppm
LMS100 SAC STIG, 50/60 Hz	Gas	Single Annular (SAC)	Steam	Steam Injection	25 ppm
LMS100 DLE, 50/60 Hz	Gas	DLE2	None	None	25 ppm

LMS100 Applications For Power Generation

LMS100 Operational Flexibility

Economic Risks Factors \ Risks Abatement Characteristics	High Simple Cycle Efficiency	High Part Power Efficiency	Cycling w/o Maintenance Impact	10 Minutes Starts	Load Following Capability	Synchronous Condenser Capability	Off-frequency Support	Dual Fuel (SAC)	Modular Construction
Fuel Price Volitility	•	•						•	
Electricty Price Volitility	•	•	•	•					
Dispatch Rank	•	•	•	•	•				
Grid Stability / Support			•	•	•	•	•		
Load Demand Variations		•	•	•	•				
Plant Outage	•	•	•	•	•		•		•

The attributes of the **LMS100** make it a versatile power generation system offering customers increased operational flexibility in a wide variety of applications:

- **Simple Cycle / Peaking & Mid-Range**...high efficiency, low first cost, sustained hot day power, 10-minute starts and no maintenance penalty for cycling, yield the ideal peaking solution. Throw in high part-power efficiency and load following capability to get high dispatch capability for mid-range applications.

- **STIG** ...steam injection for power augmentation provides significant efficiency and power improvements, as well as flexibility. With variable STIG, an operator can inject all of the steam into the gas turbine or pass the steam to process to take advantage of electricity prices or process steam value.

- **Combined Cycle** ...the low exhaust temperature leads to lower cost exhaust system materials, smaller steam turbines, condensers and generators, leading to a lower steam plant installed cost.

Another benefit from the lower exhaust temperature is more power from duct firing (up to 30MW).

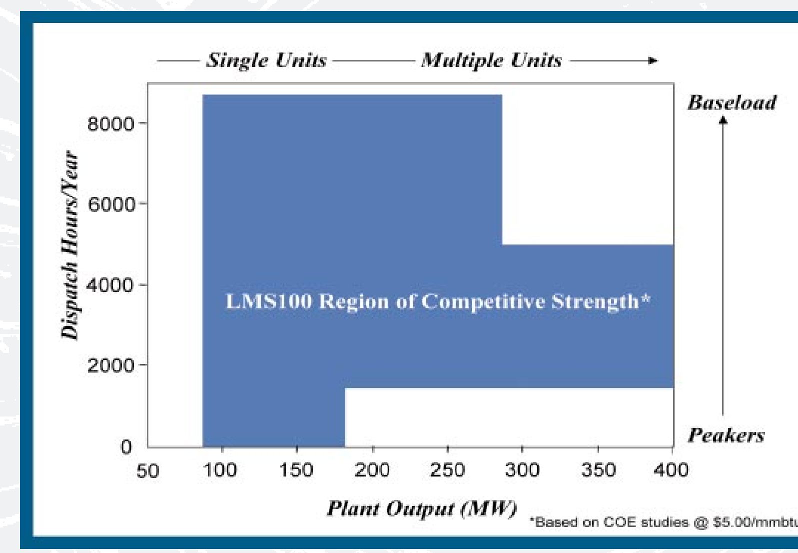
- **Combined Heat & Power** ...the high power-to-steam ratio allows the **LMS100** to meet the steam demand served by 40-50MW gas turbines while delivering more than twice the power. Using both exhaust and air-to-water intercooler energy, an LMS100 plant can reach >85% thermal efficiency.

- **50Hz and 60Hz Applications** ...the **LMS100** can operate at 50Hz and 60Hz operation without a gearbox, reducing system complexity, plot size and cost, while increasing reliability.

- **Off-Frequency Operation** ...the **LMS100** will operate with very little power variation for up to 5% reduction in grid frequency, allowing grid support in times of high demand and load fluctuations.

When your power generation need exceeds 100MW, the **LMS100** can provide an economic solution in a multi-unit arrangement by providing high efficiency power with unmatched flexibility.

LMS100 Provides Outstanding Customer Value in 80+ MW Applications



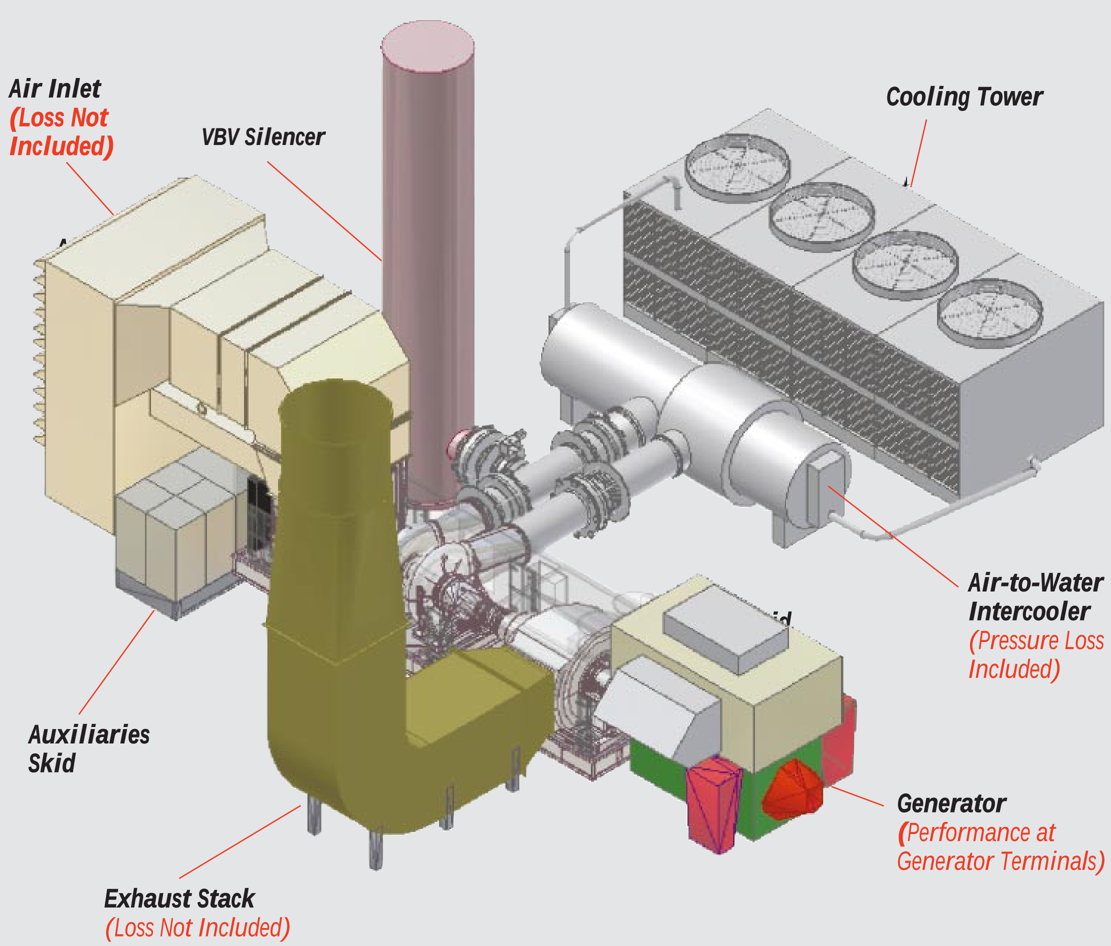
LMS100 ISO Performance Data

Simple Cycle Gas Turbine 60Hz Applications

Model	Output (MWe)	Heat Rate (BTU/KWH)	Efficiency %
DLE	98.7	7509	46
SAC (w/Water)	102.6	7813	44
SAC (w/Steam)	102.1	7167	48
STIG	112.2	6845	50

Conditions:

Performance at the generator terminals
NOx = 25 ppm
59ºF, 60% Relative Humidity
Losses: 0"/0" inlet/exhaust
Fuel: Spec. Gas (LHV = 19000 BTU/lb)



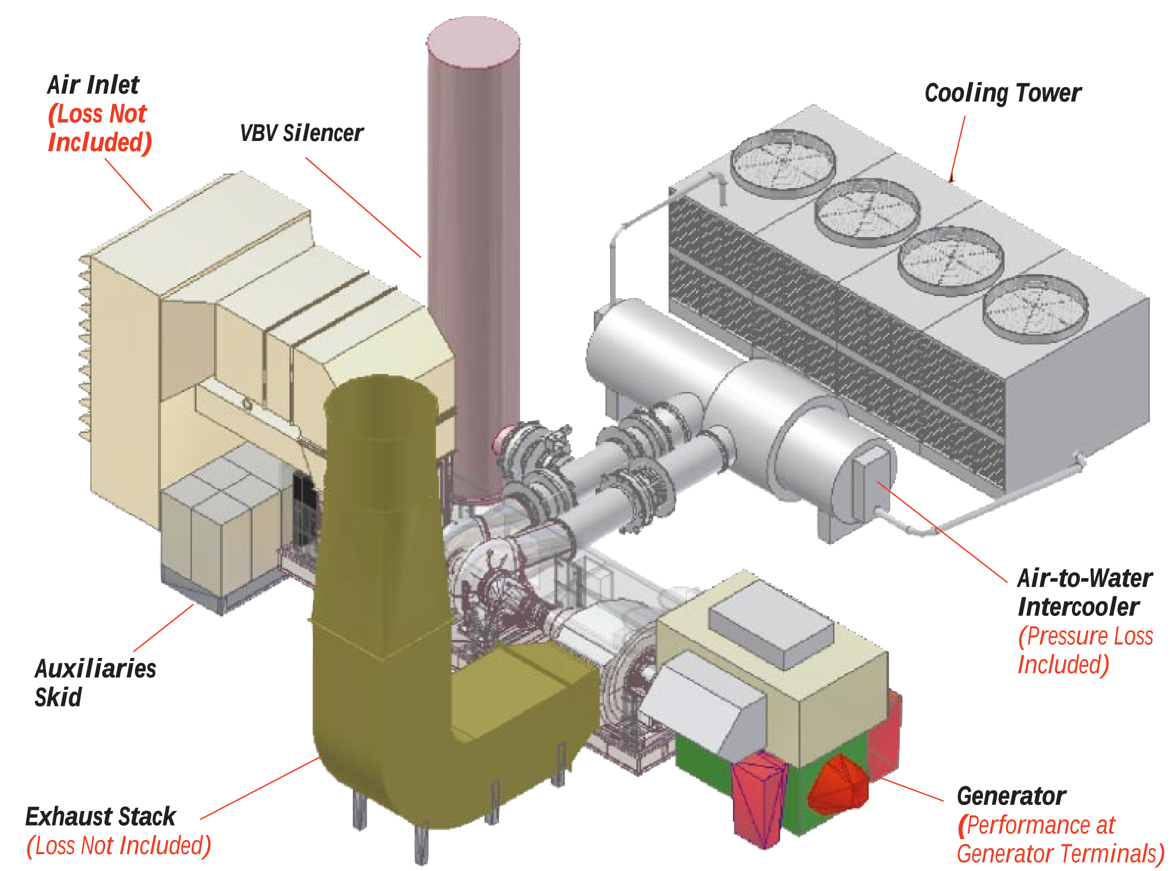
LMS100 ISO Performance Data

Simple Cycle Gas Turbine 50Hz Applications

Model	Output (MWe)	Heat Rate (KJ/KWH)	Efficiency %
DLE	99	7921	45
SAC (w/Water)	102.5	8247	44
SAC (w/Steam)	102.2	7603	47
STIG	110.8	7263	50

Conditions:

Performance at the generator terminals
NOx = 25 ppm
15ºC, 60% Relative Humidity
Losses: 0mm/0mm inlet/exhaust
Fuel: Spec Gas (LHV = 44.2MJ/KG)



GEA13640-1 (11/03)

GE Power Systems

GE Energy

New High Efficiency Simple Cycle Gas Turbine – GE's LMS100™

imagination at work

Authored by:
Michael J. Reale
LMS100™ Platform Manager

GER-4222A (06/04)
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New High Efficiency Simple Cycle Gas Turbine – GE's LMS100™

Contents:

New High Efficiency Simple Cycle Gas Turbine – GE's LMS100™

Abstract

GE has introduced the first modern production gas turbine in the power generation industry to employ off-engine intercooling technology with the use of an external heat exchanger, the LMS100™. This gas turbine provides the highest simple cycle efficiency in the Industry today and comes on the heels of GE's introduction of the highest combined cycle gas turbine system, the MS9001H. The LMS100™ system combines frame and aeroderivative gas turbine technology for gas fired power generation. This marriage provides customers with cyclic capability without maintenance impact, high simple cycle efficiency, fast starts, high availability and reliability, at low installed cost. The unique feature of this system is the use of intercooling within the compression section of the gas turbine, leveraging technology that has been used extensively in the gas and air compressor industry. Application of this technology to gas turbines has been evaluated by GE and others extensively over many years although it has never been commercialized for large power generation applications. In the past five years, GE has successfully used the SPRINT® patented spray intercooling, evaporative cooling technology between the low and high pressure compressors of the LM6000™ gas turbine, the most popular aeroderivative gas turbine in the 40 to 50MW range. GE's development of high pressure ratio aircraft gas turbines, like the GE90®, has provided the needed technology to take intercooling to production. The LMS100™ gas turbine intercooling technology provides outputs above 100MW, reaching simple cycle thermal efficiencies in excess of 46%. This represents a 10% increase over GE's most efficient simple cycle gas turbine available today, the LM6000™.

Introduction

GE chose the intercooled cycle to meet customers' need for high simple cycle efficiency. The approach to developing an intercooled gas turbine is the result of years of intercooled cycle evaluation along with knowledge developed with operation of SPRINT® technology. Matching current technology with customer requirements results in a system approach to achieving a significant improvement in simple cycle efficiency.

The development program requirement was to use existing and proven technology from both GE Transportation (formerly GE Aircraft Engines) and GE Energy (formerly GE Power Systems), and combine them into a system that provides superior simple cycle performance at competitive installed cost. All component designs and materials, including the intercooler system, have been successfully operated in similar or more severe applications. The combination of these components and systems for a production gas turbine is new in the power generation industry.

The GE Transportation CF6-80C2/80E gas turbine provided the best platform from which to develop this new product. With over 100 million hours of operating experience in both aircraft engines and industrial applications, through the LM6000™ gas turbine, the CF6® gas turbine fits the targeted size class. The intercooling process allowed for a significant increase in mass flow compared to the current LM™ product capability. Therefore, GE Energy frame units were investigated for potential Low Pressure Compressors (LPC) due to their higher mass flow designs. The MS6001FA (6FA) gas turbine compressor operates at 460 lbm/sec (209 kg/sec) and provides the best match with the CF6-80C2 High Pressure Compressor (HPC) to meet the cycle needs.

New High Efficiency Simple Cycle Gas Turbine – GE's LMS100™

The LMS100™ system includes a 3-spool gas turbine that uses an intercooler between the LPC and the HPC as shown in Fig. 1.

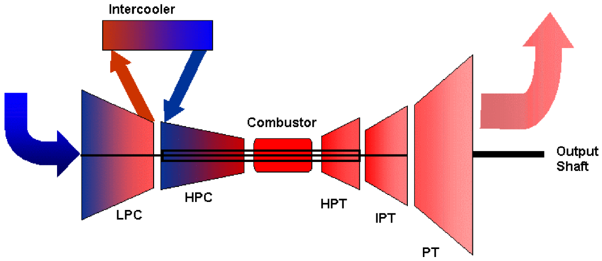

Fig. 1. LMS100™ GT Configuration

Intercooling provides significant benefits to the Brayton cycle by reducing the work of compression for the HPC, which allows for higher pressure ratios, thus increasing overall efficiency. The cycle pressure ratio is 42:1. The reduced inlet temperature for the HPC allows increased mass flow resulting in higher specific power. The lower resultant compressor discharge temperature provides colder cooling air to the turbines, which in turn allows increased firing temperatures at metal temperatures equivalent to the LM6000™ gas turbine producing increased efficiency. The LMS100™ system is a 2550°F (1380°C) firing temperature class design.

This product is particularly attractive for the peaking and mid-range dispatch applications where cyclic operation is required and efficiency becomes more important with increasing dispatch. With an aeroderivative core the LMS100™ system will operate in cyclic duty without maintenance impact. The extraordinary efficiency also provides unique capability for cogeneration applications due to the very high power-to-thermal energy ratio. Simple cycle baseload applications will benefit from the high efficiency, high availability, maintainability and low first cost.

GE, together with its program participants Avio, S.p.A., Volvo Aero Corporation and Sumitomo Corporation, are creating a product that changes the game in power generation.

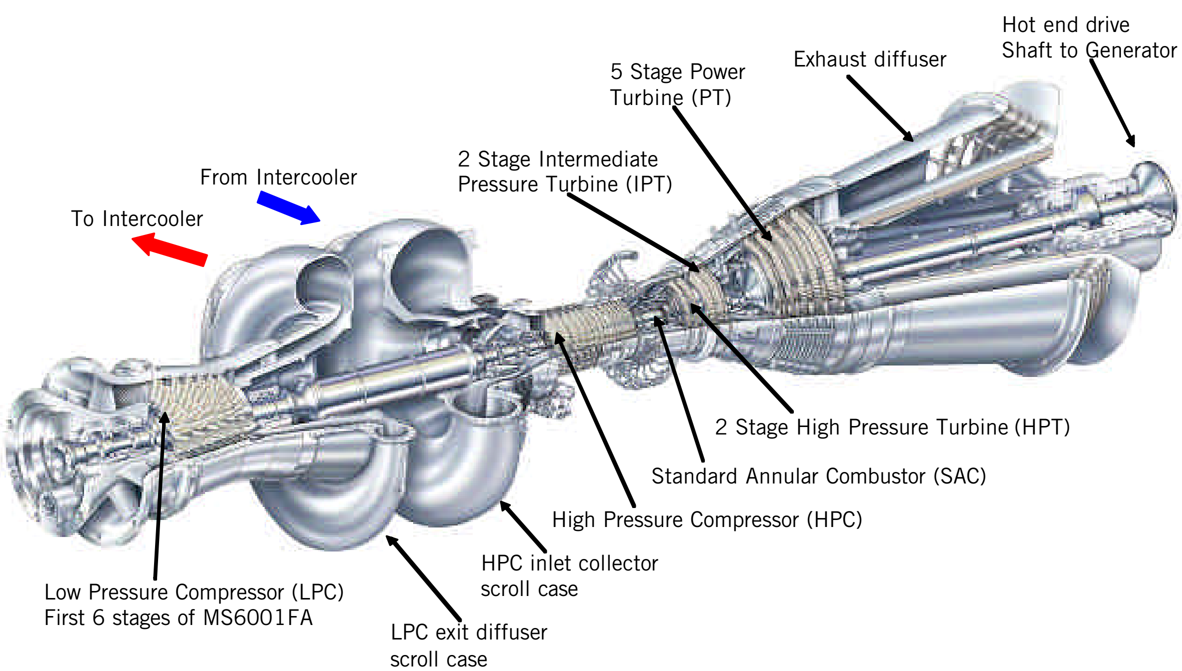

Fig. 2. LMS100™ Gas Turbine

Gas Turbine Design

The LMS100™ system combines the GE Energy FA compressor technology with GE Transportation CF6®/LM6000™ technology providing the best of both worlds to power generation customers. Fig. 2 shows the gas turbine architecture.

The LPC, which comprises the first 6 stages of the 6FA, pumps 460 lb/sec (209 kg/sec) of airflow (1.7 X the LM6000™ airflow). This flow rate matched the capability of the core engine in the intercooled cycle, making it an ideal choice. The LMS100™ system LPC operates at the same design speed as the 6FA, thereby reducing development requirements and risk. The compressor discharges through an exit guide vane and diffuser into an aerodynamically designed scroll case. The scroll case is designed to minimize pressure losses and has been validated through 1/6 scale model testing. Air leaving the scroll case is delivered to the intercooler through stainless steel piping.

Air exiting the intercooler is directed to the HPC inlet scroll case. Like the LPC exit scroll case, the HPC inlet collector scroll case is aerodynamically designed for low pressure loss. This scroll case is mechanically isolated from the HPC by an expansion bellows to eliminate loading on the case from thermal growth of the core engine.

The HPC discharges into the combustor at ~250°F (140°C) lower than the LM6000™ aeroderivative gas turbine. The combination of lower inlet temperature and less work per unit of mass flow results in a higher pressure ratio and lower discharge temperature, providing significant margin for existing material limits. The HPC airfoils and casing have been strengthened for this high pressure condition.

The combustor system will be available in two configurations: the Single Annular Combustor (SAC) is an aircraft style single dome system with water or steam injection for NOx control to 25 ppm; and the Dry Low Emissions-2 (DLE2) configuration, which is a multi-dome lean premixed design, operating dry to 25 ppm NOx and CO. The DLE2 is a new design based on the proven LM™ DLE combustor technology and the latest GE Transportation low emissions technology derived from the GE90® and CFM56® gas turbines. GE Global Research Center (GRC) is supporting the development program by providing technical expertise and conducting rig testing for the DLE2 combustor system.

The HPT module contains the latest airfoil, rotor, cooling design and materials from the CF6-80C2 and -80E aircraft engines. This design provides increased cooling flow to the critical areas of the HPT, which, in conjunction with the lower cooling flow temperatures, provides increased firing temperature capability.

The IPT drives the LPC through a mid-shaft and flexible coupling. The mid-shaft is the same design as the CF6-80C2/LM6000™. The flexible coupling is the same design used on the LM2500™ marine gas turbine on the U.S. Navy DDG-51 Destroyers. The IPT rotor and stator components are being designed, manufactured and assembled by Avio, S.p.A. as a program participant in the development of the LMS100™ system. Volvo Aero Corporation as a program participant manufactures the Intermediate Turbine Mid-Frame (TMF) and also assembles the liners, bearings and seals.

The IPT rotor/stator assembly and mid-shaft are assembled to the core engine to create the 'Supercore.' This Supercore assembly can be replaced in the field within a 24-hour period.

Lease pool Supercores will be available allowing continued operation during overhaul periods or unscheduled events.

The Power Turbine (PT) is a 5-stage design based on the LM6000™ and CF6-80C2 designs. Avio, S.p.A. is designing the PT for GE Transportation and manufacturing many of the components. Volvo Aero Corporation is designing and manufacturing the PT case. The Turbine Rear Frame (TRF) that supports the PT rotor/stator assembly and the Power Turbine Shaft Assembly (PTSA) is based on GE Energy's frame technology. The PTSA consists of a rotor and hydrodynamic tilt-pad bearings, including a thrust bearing. This system was designed by GE Energy based on extensive frame gas turbine experience. The PT rotor/stator assembly is connected to the PTSA forming a free PT (aerodynamically coupled to the Supercore), which is connected to the generator via a flexible coupling.

The diffuser and exhaust collector combination was a collaborative design effort with the aero design provided by GE Transportation and the mechanical design provided by GE Energy. GE Transportation's experience with marine modules and GE Energy's experience with E and F technology diffuser/collector designs were incorporated.

Intercooler System Design

The intercooler system consists of a heat exchanger, piping, bellows expansion joints, moisture separator and variable bleed valve (VBV) system. All process air wetted components are made of stainless steel. The LMS100™ system will be offered with two types of intercooling systems, a wet system that uses an evaporative cooling tower and a dry system (no water required).

The wet system uses an air-to-water heat exchanger of the tube and shell design, as shown in Fig. 3.

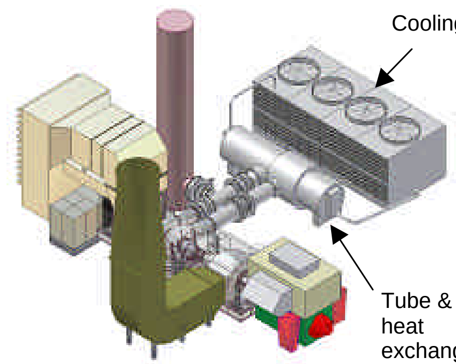

Fig. 3. LMS100™ Wet Intercooler System

The tube and shell heat exchanger is used extensively throughout the compressed air and oil & gas industries, among others. The design conditions are well within industry standards of similar-sized heat exchangers with significant industrial operating experience. This design is in general conformance with API 660 and TEMA C requirements.

The intercooler lies horizontal on supports at grade level, making maintenance very easy. Applications that have rivers, lakes or the ocean nearby can take advantage of the available cooling water. This design provides plant layout flexibility. In multi-unit sites a series of evaporative cooling towers can be constructed together, away from the GT, if desirable, to optimize the plant design.

An optional configuration using closed loop secondary cooling to a finned tube heat exchanger (replacing the evaporative cooling towers) will also be available (See Fig. 4). This design uses the same primary heat exchanger (tube and shell), piping, bellows expansion joints and VBV system, providing commonality across product configurations. The secondary cooling system can be water or glycol. This system is beneficial in cold and temperate climates or where water is scarce or expensive.

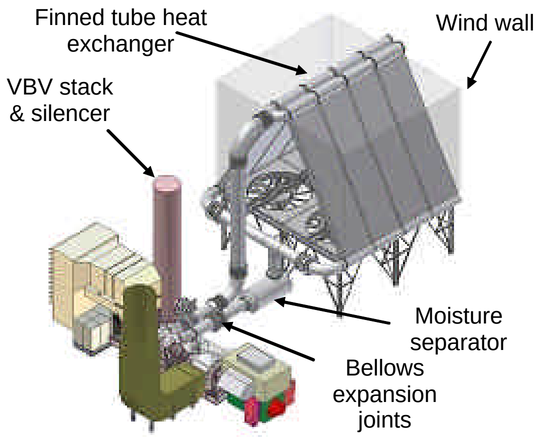

Fig. 4. LMS100™ Dry Intercooler System with Air-to-Air Heat Exchanger

An alternate dry intercooler system is being developed for future applications, and uses an air-to-air heat exchanger constructed with panels of finned tubes connected to a header manifold. This design is the same as that used with typical air-cooled systems in the industry. The main difference is mounting these panels in an A-frame configuration. This configuration is typically used with steam condensers and provides space advantages together with improved condensate drainage. The material selection, design and construction of this system are in general conformance with American Petroleum Institute (API) Standard 661 and are proven through millions of hours of operation in similar conditions.

The air-to-air system has advantages in cold weather operation since it does not require water and therefore winterization. Maintenance requirements are very low since this system has very few moving parts. In fact, below 40°F (4°C) the fans are not required, thereby eliminating the parasitic loss. In high ambient climates the performance of the air-to-air system can be enhanced with an evaporative cooling system integrated with the heat exchanger. This provides equivalent performance to the air-to-water system. Water usage will be low and intermittent since it would only be used during the peak temperature periods, resulting in a very low yearly consumption.

Package Design

The gas turbine is assembled inside a structural enclosure, which provides protection from the environment while also reducing noise (see Fig. 5). Many customer-sensing sessions were held to determine the package design requirements, which resulted in a design that has easy access for maintenance, quick replacement of the Supercore, high reliability and low installation time. Package design lessons learned from the highly successful LM6000™ gas turbine and GE's experiences with the 9H installation at Baglan Bay have been incorporated into the LMS100™ system package design. The complete GT driver package can be shipped by truck. This design significantly reduces installation time and increases reliability.

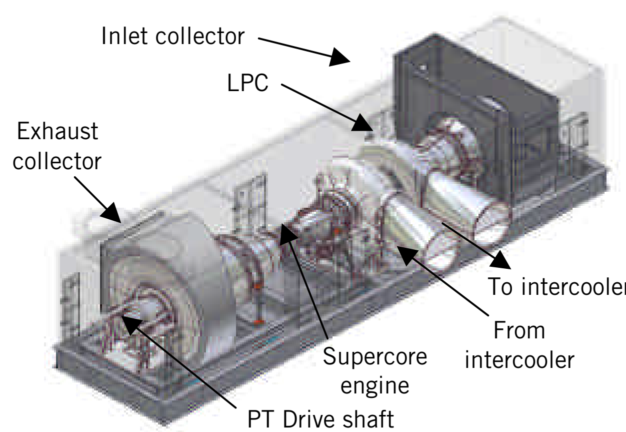

Fig. 5. LMS100™ System GT Driver Package

The auxiliary systems are mounted on a single skid in front of the GT driver package. This skid is pre-assembled and factory tested prior to shipment. The auxiliary skid connects with the base plate through short, flexible connectors. This design improves reliability and reduces interconnects and site installation cost (see Fig. 6).

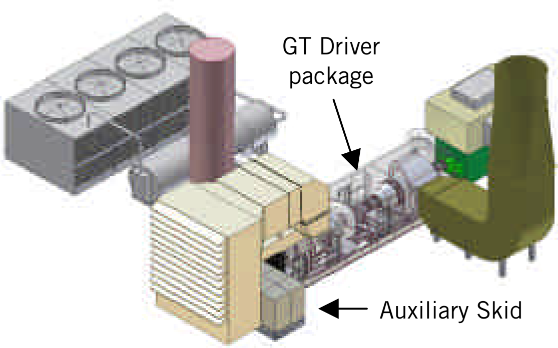

Fig. 6. LMS100™ System Auxiliary Skid Location

The control system design is a collaboration of GE Transportation and GE Energy. It employs triple processors that can be replaced on-line with redundant instrumentations and sensors. The use of GE Transportation's synthetic modeling will provide a third level of redundancy based on the successful Full Authority Digital Electronic Control (FADEC) design used in flight engines. The control system is GE Energy's new Mark VI, which will be first deployed on the LM6000™ gas turbine in late 2004 (ahead of the LMS100™ system).

The inlet system is the MS6001FA design with minor modifications to adjust for the elimination of the front-mounted generator and ventilation requirements.

The exhaust systems and intercooler systems are designed for right- or left-handed installation.

Reliability and Maintainability

The LMS100™ system is designed for high reliability and leverages LM™ and GE Energy frame technology and experience, along with GE Transportation technology. The use of Six Sigma processes and methods, and Failure Modes and Effects Analysis (FMEA) for all systems identified areas requiring redundancy or technology improvements. The LMS100™ system will consist of a single package and control system design from GE Energy, greatly enhancing reliability through commonality and simplicity.

The control system employs remote I/O (Input/Output) with the use of fiber optics for signal transmission between the package and control system. These connections are typically installed during site construction and have in the past been the source of many shutdowns due to Electro Magnetic Interference (EMI). The LMS100™ design reduces the number of these signal interconnects by 90% and eliminates EMI concerns with the use of fiber optic cables. In addition, the auxiliary skid design and location reduce the mechanical interconnects by 25%, further improving reliability. The use of an integrated system approach based on the latest reliability technology of the GE Transportation flight engine and GE Energy Frame GT will drive the Mean Time Between Forced Outages (MTBFO) of the LMS100™ system up to the best frame gas turbine rate.

The LMS100™ system has the same maintenance philosophy as aeroderivative gas turbines – modular design for field replacement. Design maintenance intervals are the same as the LM6000™ – 25,000 hours hot section repair and 50,000 hours overhaul intervals.

The LPC requires very little maintenance with only periodic borescope inspections at the same time as the core engine. No other significant maintenance is required.

The Supercore requires combustor, HPT airfoils and IPT airfoils inspection and on-condition repair or replacement at 25,000 hours. This can be accomplished on-site within a 4-day period. The package is designed for 24-hour removal and replacement of the Supercore. Rotable modules for the combustor, HPT and IPT will be used to replace existing hardware. The Supercore and PT rotor/stator module will be returned to the Depot for the 50,000-hour overhaul. During this period a leased Supercore and PT rotor/stator module will be available to continue revenue operation. The LMS100™ core is compatible with existing LM6000™ Depot capabilities.

The PT rotor/stator assembly only requires on-condition maintenance action at 50,000 hours. This module can be removed after the Supercore is removed and replaced with a new module or a leased module during this period.

The PT shaft assembly, like the LPC, needs periodic inspection only.

Configurations

The LMS100™ system is available as a Gas Turbine Generator set (GTG), which includes the complete intercooler system. An LMS100™ Simple Cycle power plant will also be offered. GTGs will be offered with several choices of combustor configurations as shown in Table 1.

The GTG is available for 50 and 60 Hz applications and does not require the use of a gearbox.

Air-to-air or air-to-water intercooler systems are available with any of the configurations to best match the site conditions.

Product Offering	Fuel Type	Diluent	NOx Level	Power Augmentation
LMS100PA-SAC (50 or 60 Hz)	Gas or Dual	Water	25	None
LMS100PA-SAC (50 or 60 Hz)	Gas	Steam	25	None
LMS100PA-SAC STIG (50 or 60 Hz)	Gas	Steam	25	Steam
LMS100PB-DLE2 (50 or 60 Hz)	Gas	None	25	None

Table 1. LMS100™ System Product Configurations

Optional kits will be made available for cold weather applications and power augmentation for hot ambient when using the air-to-air intercooler system.

All 50 Hz units will meet the requirements of applicable European directives (e.g. ATEX, PEDS, etc.).

The generator is available in an air-cooled or TWAC configuration and is dual rated (50 and 60 Hz). Sumitomo Corporation is a program participant in development of the LMS100™ system and will be supplying a portion of the production generators. Brush or others will supply generators not supplied by Sumitomo.

The GTG will be rated for 85-dBA average at 3 feet (1 meter). An option for 80-dBA average at 3 feet (1 meter) will be available.

Performance

The LMS100™ system cycle incorporates an intercooled compressor system. LPC discharge air is cooled prior to entering the HPC. This raises the specific work of the cycle from 150(kW/pps) to 210+(kW/pps). The LMS100™ system represents a significant shift in current power generation gas turbine technology (see Fig. 7 – data from Ref. 1).

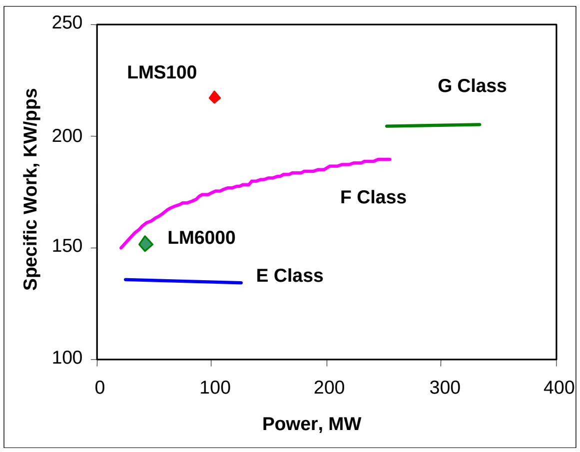

Fig. 7. LMS100™ System Specific Work vs. Other Technology

As the specific work increases for a given power the gas turbine can produce this power in a smaller turbine. This increase in technical capability leads to reduced cost. The LMS100™ system changes the game by shifting the technology curve to provide higher efficiency and power in a smaller gas turbine for its class (i.e. relative firing temperature level).

The cycle design was based on matching the existing GE Transportation CF6-80C2 compressor with available GE Energy compressor designs. The firing temperature was increased to the point allowed by the cooled high pressure air to maintain the same maximum metal temperatures as the LM6000™ gas turbine. The result is a design compression ratio of 42:1 and a firing temperature class of 2550°F (1380°C) that produces greater than 46% simple cycle gas turbine shaft efficiency. This represents a 10% increase over GE's highest efficiency gas turbine available in the Industry today – the LM6000™ gas turbine @42% (see Fig. 8 – data from Ref. 1).

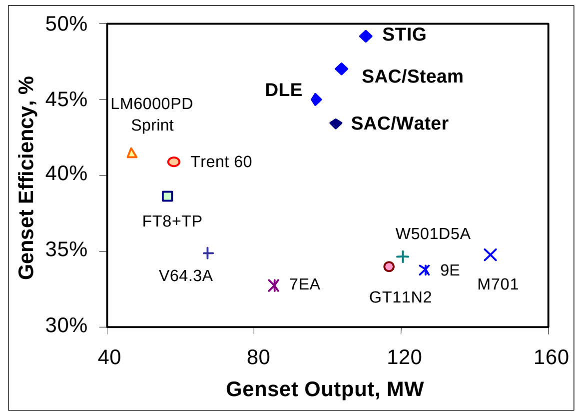

Fig. 8. LMS100™ System Competitive Positions

Intercooling provides unique attributes to the cycle. The ability to control the HPC inlet temperature to a desired temperature regardless of ambient temperatures provides operational flexibility and improved performance. The LMS100™ system with the SAC combustion system maintains a high power level up to an ambient temperature of ~80°F (27°C) (see Fig. 9). The lapse rate (rate of power reduction vs. ambient temperature) from 59°F (15°C) to 90°F (32°C) is only 2%, which is significantly less than a typical aeroderivative (~22%) or frame gas turbine (~12%).

The LMS100™ system has been designed for 50 and 60 Hz operations without the need for a speed reduction gearbox. This is achieved by providing a different PT Stage 1 nozzle for each speed that is mounted between the Supercore and PT. The PT design point is optimized to provide the best performance at both 3000 and 3600 rpm operating speeds. Fig. 9 shows that there is a very small difference in performance between the two operating speeds.

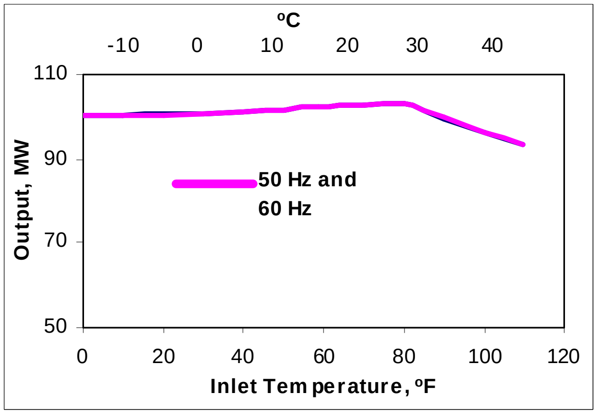

Fig. 9. LMS100™ System SAC Performance

Most countries today have increased their focus on environmental impact of new power plants and desire low emissions. Even with the high firing temperatures and pressures, the LMS100™ system is capable of 25ppm NOx at 15% O_2 dry. Table 1 shows the emission levels for each configuration. The 25 ppm NOx emissions from an LMS100™ system represent a 30% reduction in pounds of NOx/kWh relative to LM6000™ levels. The high cycle efficiency results in low exhaust temperatures and the ability to use lower temperature SCRs (Selective Catalytic Reduction).

Another unique characteristic of the LMS100™ system is the ability to achieve high part-power efficiency. Fig. 10 shows the part-power efficiency versus load. It should be noted that at 50% load the LMS100™ system heat rate (~40% efficiency) is better than most gas turbines at baseload. Also, the 59°F (15°C) and 90°F (32°C) curves are identical.

The LMS100™ system will be available in a STIG (steam injection for power augmentation) configuration providing significant efficiency improvements and power augmentation. Figs. 11 and 12 show the power output at the generator terminals and heat rate, respectively.

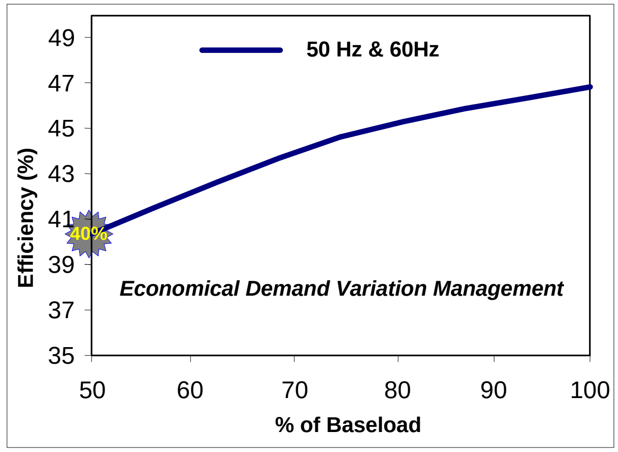

Fig. 10. LMS100™ System Part-Power Efficiency

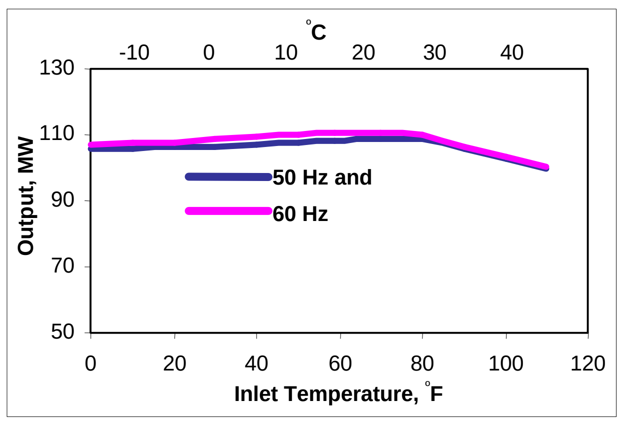

Fig. 11. LMS100™ System STIG Electric Power vs $T_{ambient}$

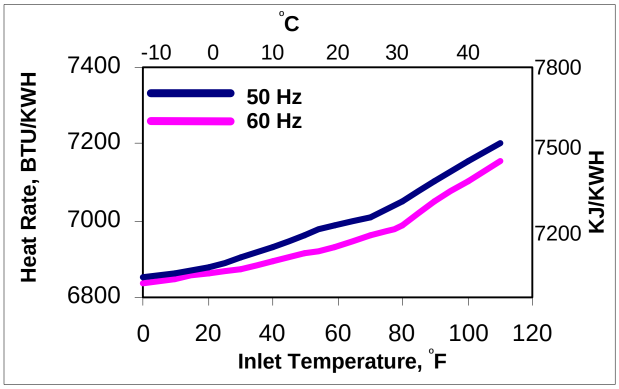

Fig. 12. **LMS100™ System STIG Heat Rate (LHV) vs $T_{ambient}$**

The use of STIG can be varied from full STIG to steam injection for NOx reduction only. The later allows steam production for process if needed. Fig. 13 – data from Ref. 1, compares the electrical power and steam production (@ 165 psi/365°F, 11.3 bar/185°C) of different technologies with the LMS100™ system variable STIG performance.

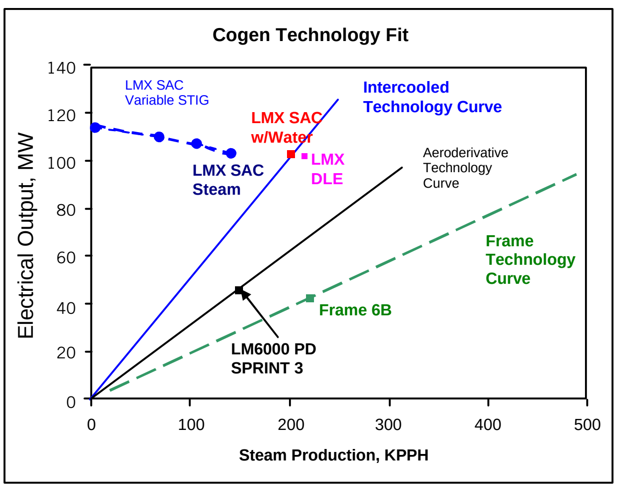

Fig. 13. **LMS100™ System Variable STIG for Cogen**

A unique characteristic of the LMS100™ system is that at >2X the power of the LM6000™ gas turbine it provides approximately the same steam flow. This steam-to-process can be varied to match heating or cooling needs for winter or summer, respectively. During the peak season, when power is needed and electricity prices are high, the steam can be injected into the gas turbine to efficiently produce additional power. During other periods the steam can be used for process. This characteristic provides flexibility to the customer and economic operation under varying conditions.

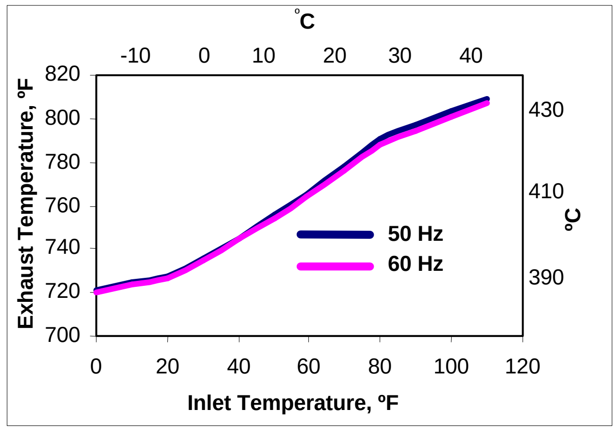

Fig. 14. **LMS100™ System Exhaust Temperatures**

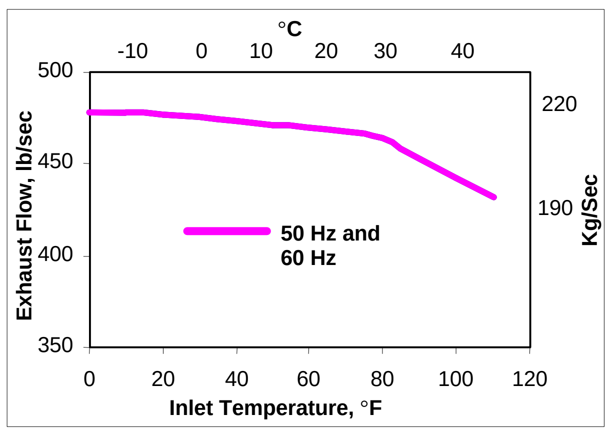

Fig. 15. **LMS100™ System Exhaust Flow**

The LMS100™ system cycle results in low exhaust temperature due to the high efficiency (see Figs. 14 and 15). Good combined cycle efficiency can be achieved with a much smaller steam plant than other gas turbines.

Table 2 shows a summary of the LMS100™ system configurations and their performance. The product flexibility provides the customer with multiple configurations to match their needs while at the same time delivering outstanding performance.

	Power (Mwe) 60 HZ	Heat Rate (BTU/KWh) 60 Hz	Power (Mwe) 50 HZ	Heat Rate (KJ/KWh) 50 Hz
DLE	98.7	7509	99.0	7921
SAC w/Water	102.6	7813	102.5	8247
SAC w/Steam	104.5	7167	102.2	7603
STIG	112.2	6845	110.8	7263

Table 2. LMS100™ System Generator Terminal Performance

(ISO 59ºF/15ºC, 60% RH, zero losses, sea level)

Simple Cycle

The LMS100™ system was primarily designed for simple cycle mid-range dispatch. However, due to its high specific work, it has low installed cost, and with no cyclic impact on maintenance cost, it is also competitive in peaking applications. In the 100 to 160MW peaking power range, the LMS100™ system provides the lowest cost-of-electricity (COE). Fig. 16 shows the range of dispatch and power demand over which the LMS100™ system serves as an economical product choice. This evaluation was based on COE analysis at $5.00/MMBTU (HHV).

The LMS100™ will be available in a DLE configuration. This configuration with a dry intercooler system will provide an environmental simple cycle power plant combining high efficiency, low mass emissions rate and without the usage of water.

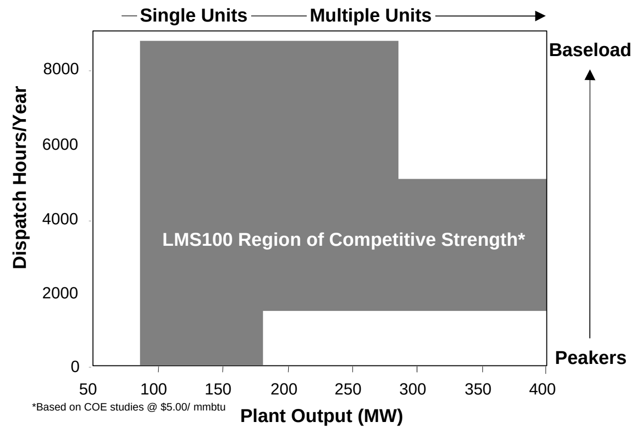

Fig. 16. LMS100™ System Competitive Regions

In simple cycle applications all frame and aeroderivative gas turbines require tempering fans in the exhaust to bring the exhaust temperature within the SCR material capability. The exhaust temperature (shown in Fig. 14) of the LMS100™ system is low enough to eliminate the requirement for tempering fans and allows use of lower cost SCRs.

Many peaking units are operated in hot ambient conditions to help meet the power demand when air conditioning use is at its maximum. High ambient temperatures usually mean lower power for gas turbines. Customers tend to evaluate gas turbines at 90ºF (32ºC) for these applications. Typically, inlet chilling is employed on aeroderivatives or evaporative cooling for heavy duty and aeroderivative engines to reduce the inlet temperature and increase power. This adds fixed cost to the power plant along with the variable cost adder for water usage. The power versus temperature profile for the LMS100™ system in

Fig. 9 shows power to be increasing to 80°F (27°C) and shows a lower lapse rate beyond that point versus other gas turbines. This eliminates the need for inlet chilling thereby reducing the product cost and parasitic losses. Evaporative cooling can be used above this point for additional power gain.

Simple cycle gas turbines, especially aeroderivatives, are typically used to support the grid by providing quick start (10 minutes to full power) and load following capability. The LMS100™ system is the only gas turbine in its size class with both of these capabilities. High part-power efficiency, as shown in Fig. 10, enhances load following by improving LMS100™ system operating economics.

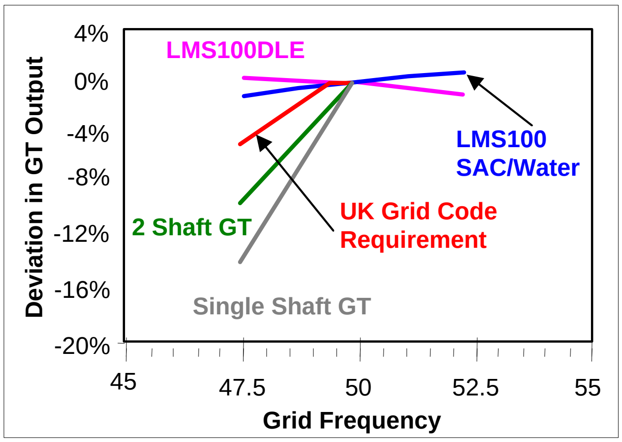

Fig. 17. LMS100™ System Gas Turbine Grid Frequency Variations

Many countries require off-frequency operation without significant power loss in order to support the grid system. The United Kingdom grid code permits no reduction in power for 1% reduction in grid frequency (49.5 Hz) and 5% reduction in power for an additional 5% reduction in grid frequency (47 Hz). Fig. 17 shows the impact of grid frequency variation on 3 different gas turbines: a single shaft, a 2-shaft and the LMS100™ system. Typically, a single and 2-shaft engine will need to derate power in order to meet the UK code requirements.

The LMS100™ system can operate with very little power variation for up to 5% grid frequency variation. This product is uniquely capable of supporting the grid in times of high demand and load fluctuations.

Combined Heat and Power

Combined Heat and Power (CHP) applications commonly use gas turbines. The exhaust energy is used to make steam for manufacturing processes and absorption chilling for air conditioning, among others. The LMS100™ system provides a unique characteristic for CHP applications. As shown in Fig. 13, the higher power-to-steam ratio can meet the demands served by 40-50MW aeroderivative and frame gas turbines and provide more than twice the power. From the opposite view, at 100MW the LMS100™ system can provide a lower amount of steam without suffering the significant efficiency reduction seen with similar size gas turbines at this steam flow. This characteristic creates opportunities for economical operation in conjunction with lower steam demand.

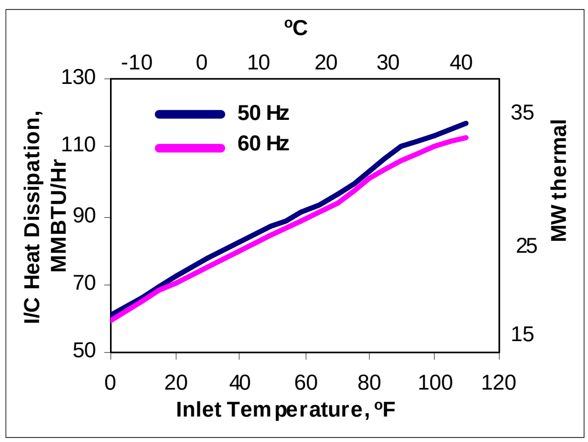

Fig. 18. LMS100™ System Intercooler Heat Rejections

Fig. 18 shows the intercooler heat dissipation, which ranges from 20-30MW of thermal energy. With an air-to-water intercooler system, the energy can be captured for low-grade steam or other applications, significantly raising the plant efficiency level. Using exhaust and intercooler energy, an LMS100™ plant will have >85% thermal efficiency.

Combined Cycle

Even though the LMS100™ system was aimed at the mid-range dispatch segment, it is also attractive in the combined cycle segment. Frame gas turbines tend to have high combined cycle efficiency due to their high exhaust temperatures. In the 80-160MW class, combined cycle efficiencies range from 51–54%. The LMS100™ system produces 120MW at 53.8% efficiency in combined cycle.

A combined cycle plant based on a frame type gas turbine produces 60-70% of the total plant power from the gas turbine and 30-40% from the steam turbine. In combined cycle the LMS100™ system produces 85-90% of the total plant power from the gas turbine and 10-15% from the steam turbine. This results in a lower installed cost for the steam plant.

The lower exhaust temperature of the LMS100™ system also allows significantly more power from exhaust system duct firing for peaking applications. Typical frame gas turbines exhaust at 1000ºF-1150ºF (538ºC-621ºC) which leaves 300ºF-350ºF (149ºC-177ºC) for duct firing. With the LMS100™ exhaust temperatures at <825ºF (440ºC) and duct-firing capability to 1450ºF (788ºC) (material limit) an additional 30MW can be produced.

Core Test

The LMS100™ core engine will test in GE Transportation's high altitude test cell in June 2004. This facility provides the required mass flow at >35 psi (>2 bar) approaching the core inlet conditions. The compressor and turbine rotor and airfoils will be fully instrumented. The core engine test will use a SAC dual fuel combustor configuration with water injection. Testing will be conducted on both gas and liquid fuel. This test will validate HPC and HPT aeromechanics, combustor characteristics, starting and part load characteristics, rotor mechanical design and aero thermal conditions, along with preliminary performance. More than 1,500 sensors will be measured during this test.

Full Load Test

The full load test will consist of validating performance (net electrical) of the gas turbine intercooler system with the production engine configuration and air-cooled generator. All mechanical systems and component designs will be validated together with the control system. The gas turbine will be operated in both steady state and transient conditions.

The full load test will be conducted at GE Energy's aeroderivative facility in Jacintoport, Texas, in the first half of 2005. The test will include a full simple cycle power plant operated to design point conditions. Power will be dissipated to air-cooled load (resistor) banks. The gas turbine will use a SAC dual fuel combustion system with water injection.

The LPC, mid-shaft, IPT and PT rotors and airfoils will be fully instrumented. The intercooler system, package and sub-systems will also be instrumented to validate design calculations. In total, over 3,000 sensors will be recorded.

After testing is complete, the Supercore and PT rotor/stator assemblies will be replaced with production (uninstrumented) hardware. The complete system will be shipped to the demonstration customer site for endurance testing. This site will be the "Fleet Leader," providing early evaluation of product reliability.

Schedule

The first production GTG will be available for shipment from GE Energy's aeroderivative facility in Jacintoport, Texas, in the second half of 2005. Configurations available at this time will be SAC gas fuel, with water or steam injection, or dual fuel with water injection. Both configurations will be available for 50 and 60 Hz applications. STIG will be available in the first half of 2006. The DLE2 combustion system development is scheduled to be complete in early 2006. Therefore, a LMS100™ system configured with DLE2 combustor in 50 or 60 Hz will be available in the second half of 2006.

Summary

The LMS100™ system provides significant benefits to power generation operators as shown in Table 3. The LMS100™ system represents a significant change in power generation technology. The marriage of frame technology and aircraft engine technology has produced unparalleled simple cycle efficiency and power generation flexibility. GE is the only company with the technology base and product experience to bring this innovative product to the power generation industry.

- High simple cycle efficiency over a wide load range
- Low lapse rate for sustained hot day power
- Low specific emissions (mass/kWh)
- 50 or 60 Hz capability without a gearbox
- Fuel flexibility – multiple combustor configurations
- Flexible power augmentation
- Designed for cyclic operation:
  - No maintenance cost impact
- 10-minute start to full power
  - Improves average efficiency in cyclic applications
  - Potential for spinning reserves credit
  - Low start-up and shutdown emissions
- Load following capability
- Synchronous condenser operation
- High availability:
  - Enabled by modular design
  - Rotable modules
  - Supercore and PT lease pool
- Low maintenance cost
- Designed for high reliability
- Flexible plant layout
  - Left- or right-hand exhaust and/or intercooler installation
- Operates economically across a wide range of dispatched hours

Table 3. LMS100™ Customer Benefits

References:

1) Gas Turbine World (GTW); "2003 GTW Handbook," Volume 23

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