Turbomachines for Application in LOTHECO Powerplants (Turbomachines for LOTHECO)

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Abstract

The improvement of the technical and economic performance of electric power generation is a continuous effort. An example is the step from simple-cycle gas turbine to combined-cycle powerplants. Later, STIG and HAT cycles were introduced and, more recently, the LOTHECO concept was proposed. This concept unites features of the standard combined-cycle powerplant and of the HAT cycle by using low-temperature external heat – and not the exhaust energy of the gas turbine – to humidify the high pressure combustion air.

An obstacle to the introduction of LOTHECO plants is the fact that in their simplest configuration they require newly designed or at least extensively modified gas turbines. This is due to the fact that the compressor and the turbine mass flow rates, when adjusted to the LOTHECO conditions, are quite different. To improve this situation, alternatives to the original LOTHECO plant with an adjusted gas turbine must be developed

It is found that combinations of standard gas turbines and expanders are solutions almost equivalent in terms of efficiency and specific work to the original LOTHECO plant with an adjusted gas turbine. Less desirable possibilities are combinations of industrial compressors and expanders.

Key Words: Combined cycles, gas turbines, expanders, specific work, efficiency

1. INTRODUCTION

LOTHECO is a relatively new combined cycle powerplant concept developed at TU Braunschweig [1]. The work presented here deals with the gas turbines of LOTHECO plants and has been performed within the framework of the EC contract ENK5-CT2000-00063. The consortium consisted of the following entities: Public Power Corporation of Greece, Technische Universitaet Braunschweig, National Technical University of Athens, Technische Universitaet Wien, Imperial College of Science Technology and Medicine, Fichtner GmbH & Co KG, Universitatea Politehnica Timisoara, Sofia Energy Centre Ltd., Frederick Institute of Technology, Electricity Authority of Cyprus and Hyperion Systems Engineering Ltd.

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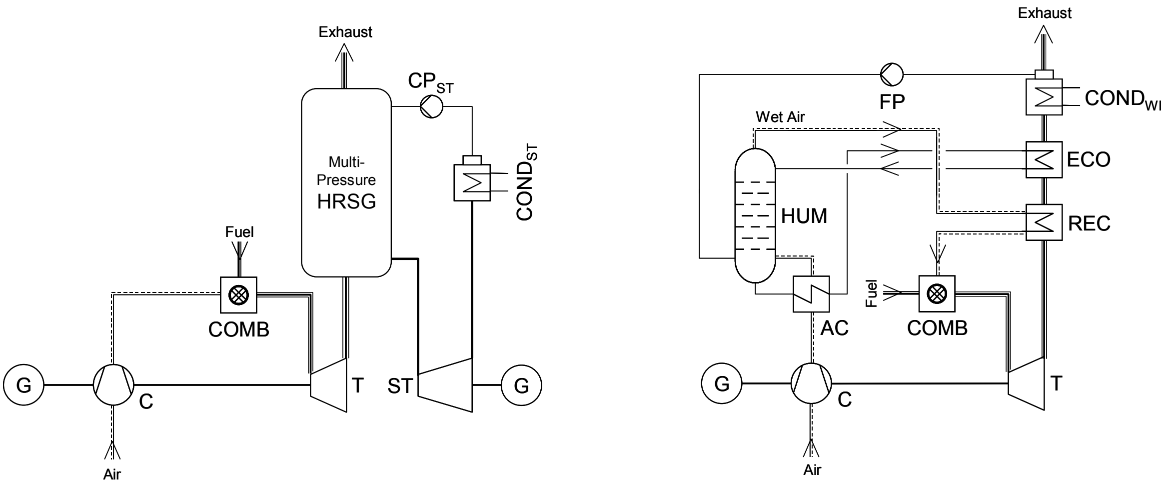
LOTHECO combines a standard combined cycle powerplant (CC) and a modified humid air turbine (HAT) cycle. In the LOTHECO cycle, the humidification is achieved by utilizing low-temperature external heat (solar radiation, waste heat from industrial processes, geothermal energy) and not the exhaust energy of the gas turbine. The corresponding simplified powerplant diagrams are shown in Figure 1.



(a) **CC**

(b) **HAT** (with partial water recovery)

(c) **LOTHECO** (with partial water recovery)

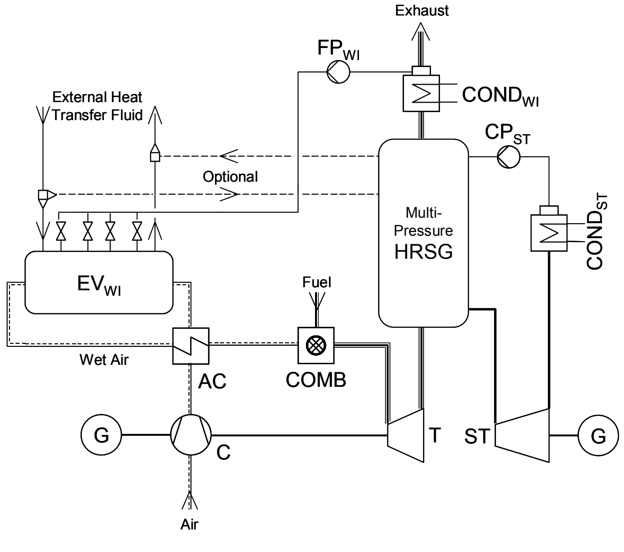


Fig 1: Simplified powerplant diagrams

In common open-cycle gas turbines fired with standard fuels such as natural gas or light fuel oil, the differences between the mass flows through the compressor, the combustion chamber, and the turbine are rather small even in the case of water injection for NO_X-reduction. The corresponding situation in HAT-cycle gas turbines is entirely different because of the great amount of water taken up in the humidifier.

Assuming a standard open-cycle gas turbine and injecting water at an increasing rate, its main components (compressor, combustor and turbine) reach critical states that must be avoided to ensure safe operation. To name but a few: compressor surge, combustor instability, critical combination of stresses and cooling of turbine vanes and blades.

Some of these effects are analyzed in the following section of this paper. Its purpose is to show that a redesign of a standard open-cycle gas turbine becomes necessary if the benefits of the HAT-cycle part of the LOTHECO cycle are to be realized.

Although the potential gains in output and thermal efficiency are significant, the corresponding redesign is very costly. Therefore, alternative arrangements of existing turbomachines are investigated in the third section of the paper.

2. LIMITATIONS OF AND MODIFICATIONS TO EXISTING OPEN-CYCLE GAS TURBINES

In this section, results are presented of simplified performance analyses of three LOTHECO powerplants.

The corresponding gas turbines have identical design compressor pressure ratios Π_{Cd}=15, identical design turbine inlet temperatures TIT_d=1300°C, and identical turbine geometries. Three compressor sizes characterized by their respective flow capacities are considered. The turbine inlet temperature of the gas turbine with the largest compressor is varied in two steps from its design value to TIT=1170°C and TIT=990°C. See Table 1.

Table 1: Identification of gas turbine operating lines in Figure 2

		Ref. Compr. Mass Flow Rate		
		1.0	0.8	0.6
Turb. Inl. T. TIT [°C]	1300	1	2	3
	1170	4		
	990	5		

The steam cycles are assumed to be dual-pressure systems.

The performance calculations are based upon generic gas turbine maps as maps of existing machines are not available. Relying on experiments conducted at the Lund Institute of Technology [2], the maximum steam-to-air ratio beyond which combustor oscillations may occur is assumed to be $\mu_{COMB} = 0.4$.

Figure 2 shows the normalized powerplant output, i.e., the sum of the gas turbine and steam-turbine outputs normalized by the gas-turbine output, plotted vs. the steam-to-air ratio.

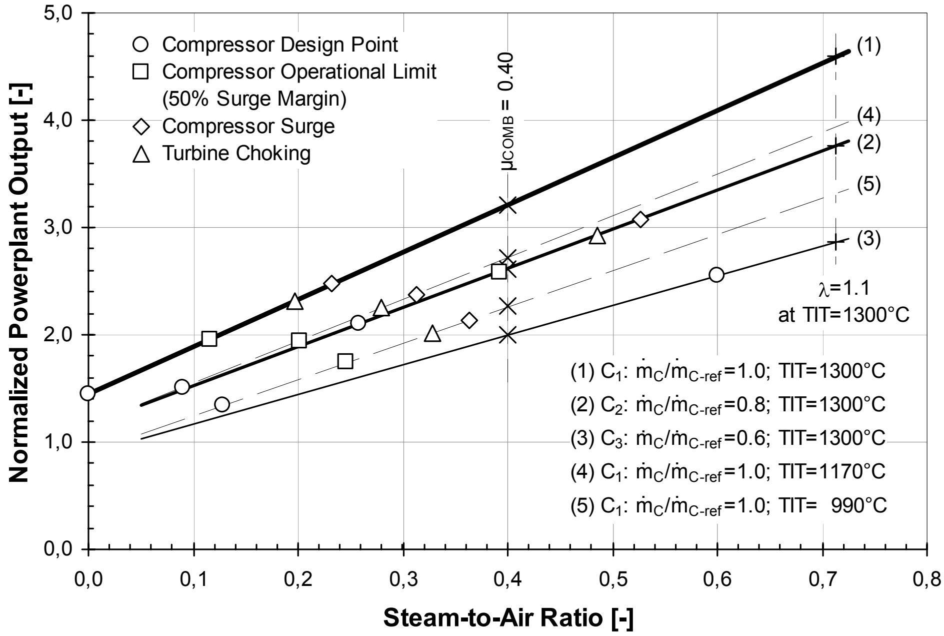


Fig 2: Gas turbine operating lines

It is seen that in a given powerplant and at constant turbine inlet temperature, identified, for example, by operating line 1, the steam-to-air ratio cannot be raised much before critical operating conditions are reached. When the turbine inlet temperature is reduced and the compressor is to operate, say, in its design point (Π_{Cd}=15), a corresponding additional steam flow must be admitted. But this does not seem to raise the normalized powerplant output appreciably. As the turbine inlet temperature continues to be reduced, the normalized powerplant output is reduced as well. The desired increase in normalized powerplant output is achieved, however, when a compressor of lower flow capacity is used in combination with the original turbine. The reverse, i.e., the original compressor and a larger turbine, applies as well.

The net powerplant efficiencies of the five configurations increase with increasing steam-to-air ratio. The slopes of the curves are greatest at low steam-to-air ratios. The efficiency maxima (0.62 to 0.64) are reached at steam-to-air ratios between 0.5 and 0.6.

Avoiding or reducing the problems indicated above requires at least a new design of the compressor or of the turbine or even a new design of one of these and a significant modification of the other. Since such changes to existing machines are very expensive, alternative concepts are now investigated.

3. ALTERNATIVE POWERPLANTS CONCEPTS AND THEIR THERMODYNAMIC POTENTIAL

In place of a newly designed adjusted gas turbine with a downscaled compressor or an upscaled turbine, the following two turbomachinery combinations seem to be promising: (a) a combination of an industrial compressor and an expander as used in process industries, and (b) a combination of a standard gas turbine and an expander.

A preliminary analysis shows the following results: The compressor-expander combination is probably the cheaper solution than the standard gas turbine-expander combination. However, it leads to a lower specific powerplant output (based on compressor air mass flow rate) and a lower thermal powerplant efficiency (based on fuel burnt) by about 40 % to 60 % and about 10 to 15 points, respectively. This result is not surprising because industrial expanders are designed for relatively moderate inlet temperatures of approximately 700 to 750°C or even less not requiring any cooling.

Therefore, the standard gas turbine (GT)-expander combination is further investigated. It can be realized by the parallel arrangement of the standard GT and the expander in three ways (Figure 3).

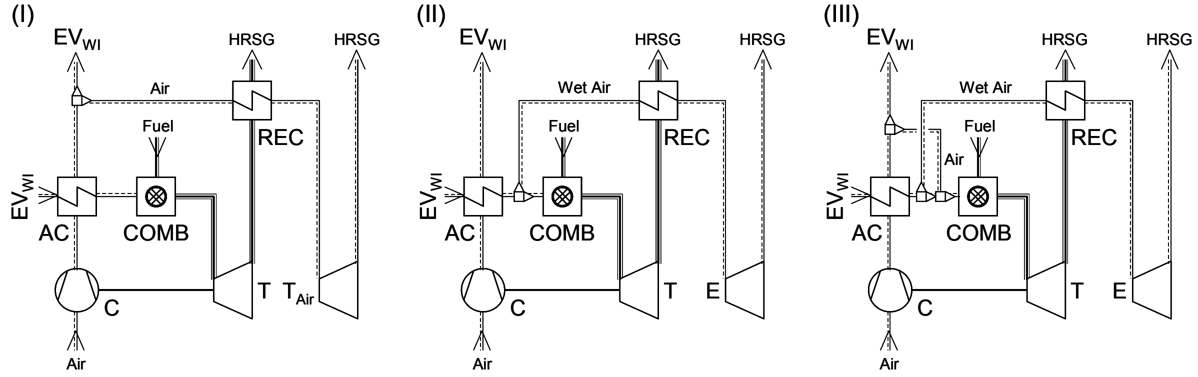


Fig 3: Arrangements of standard GT-expander combinations

Their common feature is the recuperator in which the expander flow medium is heated by the GT exhaust heat.

Their differences consist in the ways in which their respective expander flow media are composed:

(I) Combination of standard GT and air turbine (alternative I): Downstream of the aftercooler (AC), the air flow is divided. The air flow intended for the gas turbine is fed into the evaporator (EV_{WI}) where the water is injected. The remaining air flow is heated in the recuperator (REC) by the gas turbine exhaust heat and then expanded in the air turbine (T_{Air}) as mentioned above.

(II) Combination of standard GT and expander (alternative II): The working fluid is now divided in front of the combustor (COMB). As the limit of injectable water is set by the combustor [2], more water can be injected into this gas turbine cycle than into the cycle of alternative I.

(III) Combination of standard GT and expander (alternative III): This cycle is a further development of alternative II to raise the amount of injectable water. The steam content of the working fluid in the expander is restricted only by the evaporator capacity and, therefore, can exceed that of the combustor. As in alternative I, the air flow is divided downstream of the aftercooler. The main flow is directed to the evaporator generating a mixture with a high steam content.

After passing the aftercooler, it is divided into a combustor stream and an expander stream. The split-off air is added to the steam enriched combustor flow thus reducing its steam-to-air ratio to the limit set by the combustor.

The cycle analyses for a great number of design points are based on a long list of component performance data, mainly compressor and gas as well as steam turbine efficiencies, gas turbine cooling requirements, and relative pressure losses [3]. Common to all LOTHECO powerplants are the availability of external heat at 200°C and dual-pressure steam cycles. The results are presented in Figure 4 together with analogous information for standard open-cycle gas turbines, standard combined-cycle powerplants, and standard LOTHECO powerplants (with adjusted gas turbine).

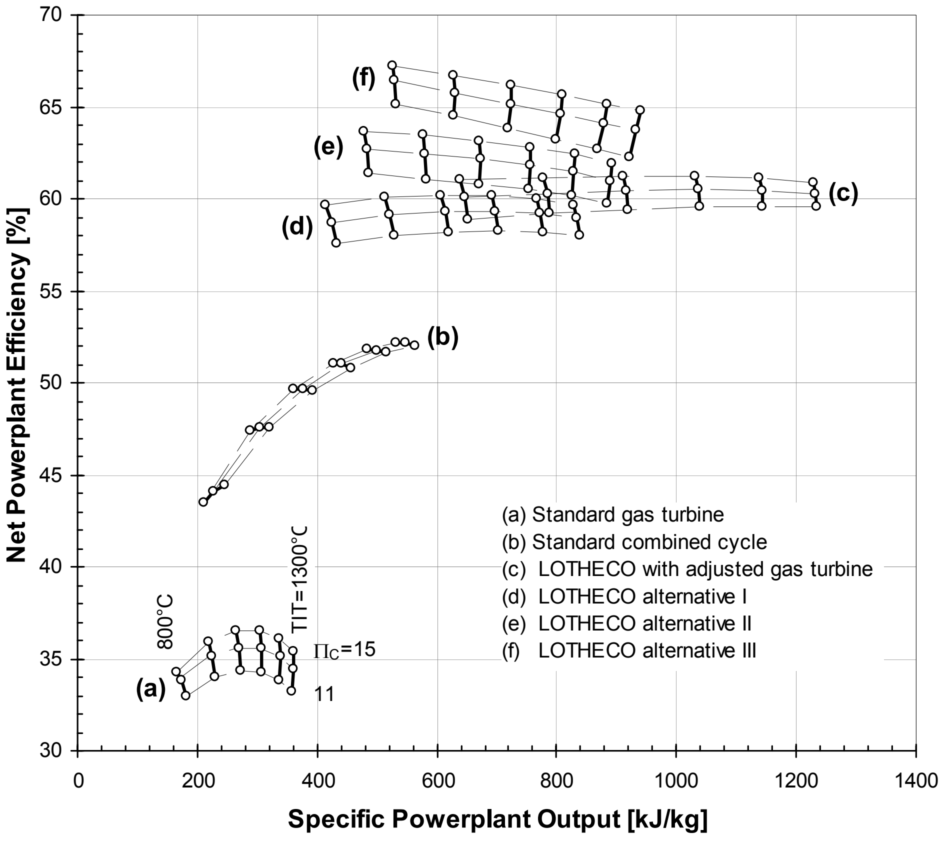


Fig 4: Comparison of cycle performance

The LOTHECO alternatives with standard open-cycle gas turbines and expanders offer almost the same or higher powerplant efficiencies than the LOTHECO powerplants with adjusted gas turbines. On the other hand, the latter perform better with respect to specific powerplant output. Nevertheless, on balance the LOTHECO alternatives can be viewed as the preferable solutions, not least because of the availability of turbomachines. However, these will require some relatively minor modifications too because of outlets and inlets required to connect them to evaporators and recuperators. In this respect, they are similar to recuperated open-cycle gas turbines.

As turbine inlet temperatures TIT of around 1300°C and compressor pressure ratios Π_c of around 15 are relatively common, their performance data are specially presented in Table 2.

Table 2: Performance of investigated powerplant schemes at TIT=1300°C and Π_C=15

Ident.	Characteristics	w_{plant}	η_{fuel}
		[kJ/kg]	[%]
(a)	Standard gas turbine (without water injection)	361	35.4
(b)	Combined cycle powerplant	542	52.2
(c)	LOTHECO with adjusted gas turbine	1252	60.9
(d)	LOTHECO alternative I (standard GT and air turbine)	844	59.7
(e)	LOTHECO alternative II (standard GT and expander)	891	61.9
(f)	LOTHECO alternative III (standard GT and expander)	942	64.7
(g)	LOTHECO with adjusted GT and integration of external low-temperature heat into the steam cycle (economizer)	1301	63.3
(h)	LOTHECO with adjusted GT and integration of external low-temperature heat into the steam cycle (LP steam generation)	1520	73.9

In Table 2, performance data are presented for two additional LOTHECO alternatives identified by **g** and **h**. They are based on adjusted gas turbines and heat transferred from the low-temperature heat source into the steam cycle. This option is indicated in Figure 1(c) by the dashed lines designated “Optional”. Although the performance is impressive, the probability of realization of such plants does not seem to be high.

Finally, in Figure 5, the distribution of the power produced by the various turbomachines is presented.

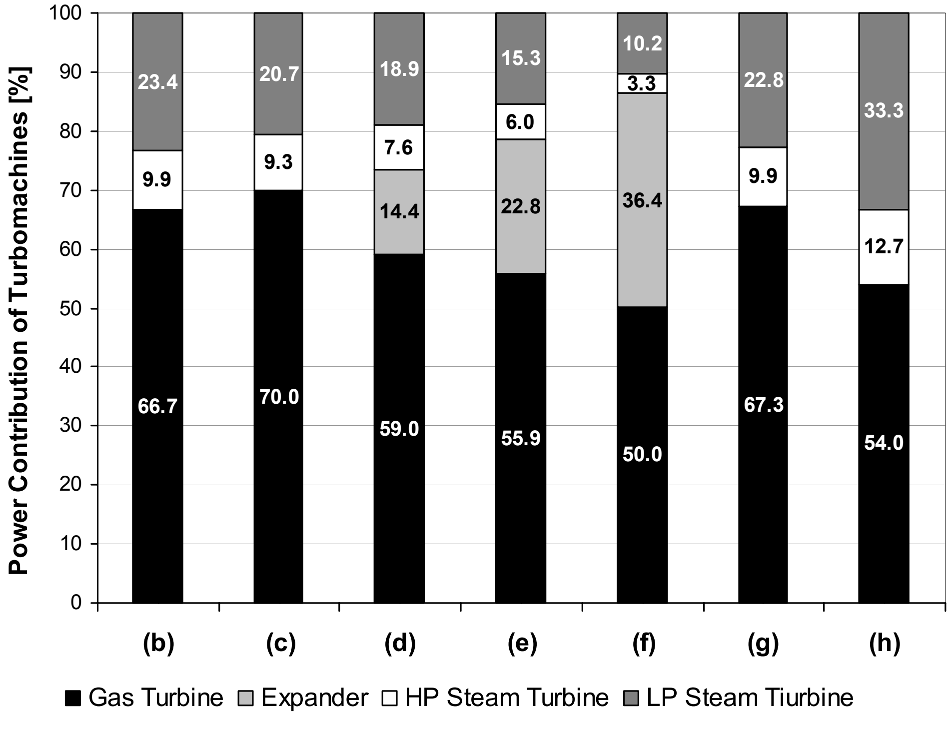


Fig 5: Contribution of thermal turbomachines to total plant output

4. CONCLUSIONS

The investigation of the basic LOTHECO concept and various alternative designs shows that there exist several obstacles to their realization. They concern mainly the application of standard gas turbines because of their limited tolerance to the large difference between compressor and turbine mass flow rates.

The analyses of modified concepts indicate that combinations of standard gas turbines and expanders are a better choice because the gas turbines require comparatively fewer and much simpler design modifications and expanders are common turbomachines in process industries. With respect to performance, there alternative LOTHECO concepts are equal to the originally proposed one in terms of efficiency. The specific powerplant outputs of the alternative concepts are smaller than that of the original one.

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Nomenclature

AC	aftercooler	FP	feed pump
C	compressor	G	generator
COMB	combustor, combustion chamber	HRSG	heat recovery steam generator
COND	condensor	HUM	humidifier
CP	condensate pump	REC	recuperator
E	expander	ST	steam turbine
ECO	economizer	T	turbine
EV	evaporator	TIT	turbine inlet temperature

Greek symbols

λ	reciprocal of equivalence ratio
μ	steam-to-air ratio (ratio of the steam-to-air mass flow rates)
Π	pressure ratio

Indices

C	compressor
d	design
ST	steam turbine
T	turbine
WI	injected water