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Kam gre razvoj plinskih turbin

In What Direction is the Development of Gas Turbines Heading

MARKO PERKAVEC

Kombinirani energetski postroji s plinskimi in parnimi turbinami ponujajo svetu možnost oskrbe z električno energijo ob najboljših izkoristkih in hkratnem okrepljenem varstvu okolja. Izpopolnjeni zgorevalni sistemi plinskih turbin omogočajo zelo majhne emisije škodljivih snovi v okolico, dobri izkoristki njihovih komponent ne samo ohranjajo fosilna goriva za kasnejše čase, ampak tudi zmanjšujejo učinek tople grede.

Kontinuirani razvoj zadnjih let je omogočil izkoristke kombiniranih procesov do 58 odstotkov in dvignil razpoložljivost postrojev do 98 odstotkov. V primeru kogeneracije električne energije in procesne toplote oziroma toplote za ogrevanje je mogoča izraba goriva celo do 90 odstotkov.

Omenjene vrednosti so postale stvarne šele z razvojem plinske turbine do današnje stopnje. Pri tem je treba omeniti, da je aerodinamični razvoj turbostroja dosegel precej visoko točko na asimptoti in na tem polju ni več veliko možnosti za nadaljnje izboljšave. V termodinamiki procesa pa tičijo še omembe vredne zaloge.

Pogled v prihodnost je vedno bolj ali manj meglen in povezan z negotovostjo, če hočemo izvedeti, kaj se nam obeta. To velja še posebej za pojave na polju energetike. Preveč je med seboj neodvisnih dejavnikov, ki vplivajo na razvoj trga, da bi bila napoved lahko zanesljiva. Trg namreč narekuje razvoj — in ne narobe — in daje velika investicijska sredstva, ki so zanj potrebna.

Tvegam poskus, da s pogledom naprej in z analizo razvoja v preteklih 10 do 15 letih podam napoved razvoja plinskih turbin do konca tega ter za nekaj let prihodnjega stoletja.

Combined power plants with gas and steam turbines offer the world the possibility of electrical power supply with the highest efficiency and simultaneous intensive environmental protection. Improved combustion sytems of gas turbines enable very low emissions of harmful substances into the environment, while the high efficiency of their components not only preserves fossil fuels for later generations but also lessens the greenhouse effect.

Continuous development over the past years has enabled efficiencies of combined cycles of up to 58% and raised the availability of plants to 98%. In the case of cogeneration of electrical power and heat, i.e. process heat and for district heating, fuel efficiency as high as up to 90% is possible.

Mentioned values have become realistic only with the development of gas turbines to the present level. It needs to be mentioned, however, that the aerodynamic development of turbomachinery has reached quite a high point on the asymptotic line and not many possibilities for further improvement remain in this area. There are, however, significant possibilities for further improvement in the thermodynamics of the process.

Looking into the future is always a more or less hazy and uncertain prospect, especially if one desires to find out what is in store. This is especially true in the field of power production. There are too many mutually independent factors which influence the development of the market to allow a reliable prognosis. It is the market which dictates development — and not vice versa — and makes available the large investment funds required for it.

Taking a look ahead and analysing the development over the past 10 to 15 years, I shall take a risk and make a forecast for the future development of gas turbines for the end of this and a few years of the coming century.

0 UVOD

V državah Evrope je energetsko gospodarstvo zelo različno. Norveška, Avstrija, Švica in Islandija izrabljajo pretežno vodno moč, Velika Britanija, Grčija in Nemčija v glavnem lasten premog, Francija in Belgija v veliki večini jedrsko energijo, čeprav imajo svoj premog. Danska uporablja cenen uvožen premog. Rusija in Nizozemska imata dovolj virov zemeljskega plina in zato pridobivata elektriko z njim. Italija in Portugalska uporabljata v veliki meri kurilno olje. Stanje na svetovnem trgu ni prav nič manj pisano.

Leta 1993 je znašala skupna instalirana moč energetskih naprav na svetu 2800 GW. V naslednjih 10 letih naj bi se to število zvečevalo povprečno po tri odstotke na leto, kar pomeni gradnjo nadaljnjih nekaj manj ko 90 GW na leto. 20 odstotkov novih gradenj naj bi bile jedrske in vodne centrale in 80 odstotkov naj bi prišlo na toplotne centrale (preglednica 1).

0 INTRODUCTION

Power economics in European countries varies considerably from one country to another. Norway, Austria, Switzerland and Iceland predominantly exploit their water power, Great Britain, Greece and Germany mainly use their own coal, France and Belgium mainly nuclear power, even though they have their own coal, while Denmark uses cheap imported coal. Russia and the Netherlands have sufficient sources of natural gas and therefore use it to produce electricity. Italy and Portugal use oil to a large extent. The situation in the global market is no less colourful.

In 1993 the total installed power of all power plants in the world was 2800 GW. In the following 10 years this figure should increase at an average of 3% per year, which means the installation of a further slightly less than 90 GW yearly. 20% of new installations are planned to be nuclear and hydro power plants, while 80% should be thermal power plants (Table 1).

Preglednica 1: *Delež različnih postopkov za oskrbo sveta z električno energijo leta 2005*
Table 1: *The share of various procedures in the global electrical power supply in 2005*

Proces/ Process	Delež/Share 1995	Napoved/Forecast 2005
Hidrocentrale/Hydro power plants	13	15
Jedrske centrale/Nuclear power plants	10	10
Termične centrale - samo parne turbine Thermal power plants - steam turbines only	39	30
Termične centrale - samo plinske turbine Thermal power plants - gas turbines only	17	10
Kombinirane termične centrale Combined thermal power plants	21	35

Pred letom 1980 je bil delež kombiniranih postrojev med toplotnimi centralami minimalen. Leta 1990 je dosegel že eno tretjino naročil in napovedi pravijo, da se bo njihov delež v prihodnjih nekaj letih zvečal na 60 odstotkov vseh naročenih toplotnih postrojev, kar pomeni, da bodo plinske turbine številčnejše od doslej prevladujočih velikih postrojev s parnimi turbinami.

Ta svetovna usmeritev pa je bila doslej v Evropi potrjena samo v Veliki Britaniji in na Nizozemskem. V Veliki Britaniji je bilo po privatizaciji na novo nameščenih 10000 MW v kombiniranih postrojih. Naslednja država s povečanim deležem kombiniranih postrojev utegne biti Nemčija, kjer je bilo instaliranih v zadnjih treh letih po 1000 MW kombiniranih postrojev na leto.

OECD napoveduje zvečanje porabe električne energije v zahodni Evropi do leta 2000 za povprečno 1,8 odstotka na leto. Vendar je v Nemčiji poraba električne energije leta 1993 v nasprotju s tem trendom v primerjavi z letom poprej padla za 0,5 odstotka. V letu 1995 pa pričakujejo ponovno povečanje porabe.

Before 1980, the share of combined plants among thermal power plants was minimal. In 1990 it had already achieved one third of orders and it is expected that in a few years their share will increase to 60% of all thermal plant orders, which means that gas turbine technology will overtake the presently dominant large steam turbine plants.

In Europe, this global trend has been confirmed only in Great Britain and the Netherlands. In the Great Britain, 10,000 MW have been installed in combined plants since privatisation. Another country with a growing share of combined plants is Germany, where in the past three years 1,000 MW of combined plants have been installed every year.

The OECD forecast for the growth of electrical power consumption in Western Europe by 2000 is 1.8% per year on average. But in contrast with this trend, in Germany the consumption of electrical power in 1993 in comparison with the year before dropped by 0.5%. In 1995, however, a turn of the trend towards a renewed growth of consumption is expected.

1 STANJE TEHNIKE

1.1 Plinske turbine

Današnja tehnika plinskih turbin omogoča pri velikih plinskih turbinah v enostavnem krožnem procesu odlične izkoristke na sponkah generatorja od 36 do 38 odstotkov in pri industrializiranih letalskih motorjih celo do 40 odstotkov. Pri plinskih turbinah manjše moči pa je treba računati z za dva ali tri odstotke nižjimi izkoristki.

V preglednici 2 so navedeni podatki najnovejših plinskih turbin, ki so jih najavili vodilni izdelovalci. Pri tem pade v oči, da General Electric (GE) kot pobudnik razvoja tehnologije F in vodilni izdelovalec plinskih turbin, s svojim modelom 9FA, ki je še pred tremi leti pomenil absolutni vrh, ni več prav na vrhu. Vendar je treba priznati, da GE kot edini lahko pokaže veliko število prodanih in obratujočih plinskih turbin tega razreda. Pričakovati pa je, da bo tudi GE v kratkem najavil nove modele s tehnologijo G in znova prevzel vodstvo. Razvoj je pač zelo hiter**).

Spodaj navedene že zelo velike vrednosti so bile dosežene v glavnem s povečanjem tlačnega razmerja in temperature pred turbino, pri čemer so izboljšane metode hlajenja več pripomogle k uspehu kakor boljši materiali.

1 THE STATE OF TECHNOLOGY

1.1 Gas turbines

The present technology of gas turbines enables excellent efficiencies in large gas turbines on generator terminals in simple cycles of 36 to 38% and even up to 40% in industrialised aircraft engines (aero derivatives). In gas turbines with lower power output, 2 to 3% lower efficiencies should be expected.

Table 2 lists data for the newest gas turbines announced by leading manufacturers as of summer 1995. It is notable that General Electric (GE) as the initiator of development of F technology and a leading manufacturer of gas turbines is no longer at the very top with their model 9FA, which was the absolute top only three years ago. One must admit, though, that GE is the only manufacturer which can boast of a high number of sold and operating gas turbines of this class. GE, however, is expected to announce new models using G-technology and thus once again assume the leading role. Development is moving very quickly**).

The below values, which are very high, were achieved mainly through an increase in the pressure ratio and firing temperature, whereby effective methods of cooling contributed more to success than the use of better materials.

Preglednica 2: *Primerjava nekaterih najnovejših plinskih turbin*

Table 2: *Comparison of some gas turbines using the latest technology*

	Asea Brown Boveri	GE/EGT	GE	Siemens	Westinghouse
Model/Model	GT24/ GT26	7FA/9FA*)	LM6000	V84.3A/ V94.3A	501G/ 701G
tehnika/technology	(F)	F	F	F	G
moč EPK/power SC	165/240	159/226	41.3	170/240	230/310
moč KKP/power CC	250/360	241/348	56.4	254/359	345/465
izkoristek EKP/efficiency SC	37.5/37.8 %	35.9/35.7 %	39.6 %	38.0 %	38.5 %
izkoristek KKP/efficiency CC	58.1/58.5 %	54.6/55.1 %	54.3 %	57.9/58.1 %	58.0 %
tlačno razmerje/pressure ratio	30	15	29.3	16.0	19.2
temp. pred turbino (ISO)/ firing temperature (ISO)	1360 °C (1235)	1288 °C (1190)	1300 °C (1196)	1310 °C (1190)	1427 °C (1260)
tok izpušnih plinov exhaust gas flow	376/542	427/614	124	454/640	545/780
temp. izpušnih plinov exhaust gas temperature	610 °C	589 °C	479 °C	562 °C	593 °C
prodanih/v obratovanju (pribl.) sold / in operation (approximate figures as of summer 1995)	2 / 0	90 / 15	10 / 3	7 / 0	2 / 0

*) Ti podatki so neto (pri upoštevanju vseh izgub), vsi drugo pa bruto.
This are net data (taking into account all losses); all other data are gross.

**) To se je medtem zgodilo: tehnologija E in H sta najavljeni in nekatere napovedi so že sedaj izpolnjene.
This happened in-between: the E and H technologies are announced and some of the predictions are already fullfilled.

Preglednica 2a: *Primerjava nekaterih najnovejših plinskih turbin (nadalj.)*
Table 2a: *Comparison of some gas turbines using the latest technology (contd.)*

	Westinghouse	Westinghouse	Westinghouse
Model/Model	Trent •)	501FA	501G/701G
tehnologija/technology	G	F	G
moč EKP/power SC	51.2	162	230/310
moč KKP/power CC	65.9	248	345/465
izkoristek EKP/efficiency SC	41.6	35.7	38.5
izkoristek EKP/efficiency CC	54.1	54.6	58.0
tlačno razmerje/pressure ratio	35.0	14.0	19.2
temp. pred turbino (ISO)/ firing temperature (ISO)	1250 °C (1160)	1288 °C (1170)	1427 °C (1260)
tok izpušnih plinov exhaust gas flow	160	436	545/780
templ. zgorelih plinov exhaust gas temperature	427 °C	584 °C	593 °C
prodanih/v obratovanju (pribl.) sold / in operation (approximate figures)	0 / 0	20/7	2 / 0

•) Najavljen model, v sodelovanju z Rolls Royce.
•) Announced model, in cooperation with Rolls Royce.

1.2 Kombinirani postroji

Visoka temperatura izpušnih plinov tako rekoč zahteva uporabo njihove energije. Le tako je mogoče občutno povečati izrabo goriva. Najpreprostejši postopek je postavitev parnega kotla na odpadno toploto (PKOT) v izpušni kanal plinske turbine in vodenje v njem pridobljene pare v parno turbino, ki poganja generator. Parni proces se lahko izboljša z izbiro dvo- ali tritlačnega sistema.

Kombinirani postroji velikosti 400 MW dosežejo danes s tritlačnimi sistemi in enojnim predgrevanjem izkoristke do 58 odstotkov neto.

Ker je v kombiniranem postroju moč plinske in parne turbine v razmerju približno 2:1, navadno dve plinski turbini, vsaka s svojim PKOT, dobavljata paro eni parni turbini. Tako imajo vsi generatorji enako moč.

Zelo zanimiva alternativa je postavitev plinske in parne turbine ter generatorja na eno gred. To je zelo kompaktna in preprosta izvedba, pri kateri je mogoča regulacija samo s plinsko turbino. Vendar je pri zagonu potrebna pomožna energija za vzpostavitev vakuuma v parnem sistemu.

Razpoložljivost kombiniranih postrojev je v zadnjih letih dosegla 96 odstotkov, ki jih skorajda ni več mogoče izboljšati.

1.2 Combined plants

The high temperature of exhaust gases practically dictates the use of their energy. Only in this way is it possible to appreciably increase fuel efficiency. The simplest procedure is the installation of an exhaust heat boiler into the exhaust duct of a gas turbine and leading of the steam produced in it into a steam turbine which drives a generator. The steam cycle can be improved with a selection of a 2- or 3-pressure systems.

Combined plants with a capacity of up to 400 MW nowadays achieve net efficiencies up to 58% with 3-pressure systems and single preheating.

Since in a combined plant the approximate ratio of the gas to the steam turbine power output is 2:1, two gas turbines, each with its own exhaust heat boiler, usually supply steam to one steam turbine. In this way all these generators have equal power.

A very interesting alternative is the installation of a gas turbine, a steam turbine and a generator onto one shaft. This design is very compact and simple, and regulation is possible only through the gas turbine. Nevertheless, for start-up, additional power is required for the establishing of a vacuum in the steam system.

The availability of combined plants has reached 96% in recent years and this figure almost cannot be further improved.

2 RAZVOJNI POTENCIAL

2.1 Plinske turbine

Oba turbostroja, ki sta združena v plinsko turbino, kompresor in sama turbina, sta že sedaj na zelo visoki razvojni stopnji. Preračun lopatja je tako izpopolnjen in mehanizmi izgub tako raziskani, da ni več mogoče pričakovati bistvenih izboljšav izkoristkov posameznih delov.

Vendar je treba poudariti, da v plinskem agregatu z 250 MW moči obratuje aksialni kompresor, ki potrebuje 500 MW pogonske moči in turbina s 750 MW moči. Pri tolikšnih enotah se vsaka majhna izboljšava vendarle pozna: vsaka izboljšava na kompresorju se pozna dvojno in tista na turbini trojno. Torej bo razvoj še naprej tekel v smeri izboljšave profilov lopatic, minimiranja primarnih in sekundarnih izgub ipd.

Velike specifične moči modernih plinskih turbin so mogoče samo z uporabo nadzvočnih stopenj v kompresorjih. Nadzvočne stopnje so del današnje tehnologije, vendarle jih je še mogoče izboljšati.

Največje možnosti za izboljšavo tičijo nedvomno v termodinamiki krožnega procesa plinske turbine. Pričakujemo lahko povišanje temperature pred turbino od današnjih 1300 °C na več ko 1500 °C v prihodnjih 10 letih in še 200 °C več pri industrializiranih letalskih motorjih. To povišanje bo mogoče z uvedbo intenzivnejšega hlajenja pri hkratni uporabi boljših materialov in učinkovitejših zaščitnih prevlek.

Uporaba v lastnem kompresorju komprimiranega zraka za hlajenje delov plinske turbine, ki pridejo v stik z vročimi plini, občutno zniža izkoristek plinske turbine. Že pri današnjih plinskih turbinah, s temperaturo pred turbino blizu 1300 °C, je treba kljub prefinjenim postopkom hlajenja izločiti iz glavnega toka 10 do 20 odstotkov zraka.

Vmesno hlajenje hladilnega zraka bi zmanjšalo potrebno količino in s tem povečalo izkoristek plinske turbine. Še boljša rešitev je uporaba zunanjega hladilnega sredstva (npr. voda ali para), vendar take rešitve povečajo zapletenost postroja in gredo v breme zanesljivosti in preprostega obratovanja. Kljub temu je pričakovati v bližnji prihodnosti njihovo splošno uporabo.

Kar najkrajša pot vročih plinov skozi plinsko turbino pomeni tudi manj hlajenja. Nagnjenje k obročnim komoram zgorevanja, ki ga lahko opazimo pri vseh izdelovalcih, je rezultat tega dejstva.

Nadaljnje zvišanje temperature pred turbino bo mogoče tudi z uvedbo boljših materialov in boljših prevlek komponent, ki pridejo v stik z vročimi plini. Že na današnji temperaturni ravni so v uporabi lopatice z usmerjeno kristaliziranimi materiali ali pa celo enokristalne lopatice.

2 DEVELOPMENTAL POTENTIAL

2.1 Gas turbines

Both turbo engines integrated into a gas turbine, the compressor and the turbine itself, have already achieved a very high level of development. The design of blading has been so well perfected and mechanisms of loss prediction so well researched that no essential improvements in component efficiencies can be expected.

It must be emphasised, however, that an axial compressor which requires 500 MW of driving power and a turbine with a power output of 750 MW operate in a gas turbine with a net power output of only 250 W. With such figures, every small improvement is nevertheless noticeable: each improvement of the compressor has a double effect and an improvement of the turbine has a triple effect. Development will therefore continue to run in the direction of improvement of blade profiles, minimisation of primary and secondary losses, etc.

Large specific powers of modern gas turbines are possible only with the use of transsonic stages in compressors. Transsonic stages are a part of present technology, but they still have potential for improvement.

The largest potential for improvement undoubtedly lies in the thermodynamics of the cycles for gas turbines. An increase of firing temperature can be expected for gas turbines from 1300 °C at present to over 1500 °C in the next 10 years and a further 200 °C in aero derivatives. This increase will be possible with the introduction of more intensive cooling and with a simultaneous use of better materials and more effective protective coatings.

The use of air compressed in the gas turbine's compressor for cooling parts of the gas turbine which come into contact with hot gases substantially reduces the efficiency of the gas turbine. In spite of sophisticated cooling procedures in present gas turbines in which the firing temperature reaches nearly 1300 °C, 10 to 20 % of air must be extracted from the main flow.

Intermediate cooling of cooling air would reduce the required amount of it and thereby increase the efficiency of the gas turbine. An even better solution is the use of an external cooling agent (e.g. water or steam), but such solutions increase the complexity of the plant and have a negative effect on reliability and simple operation. In spite of this, their general use can be expected in the near future.

The shortest path of hot gases through the gas turbine also means lesser cooling. The trend towards annular combustors which can be noticed in all manufacturers is last but not least a result of this fact.

A further increase in the firing temperature will become possible with the introduction of better materials and better coatings of components which come into contact with hot gases. Already with the present temperature level, blades with directionally solidified materials or even single crystal blades are used.

Iskanje še boljših materialov in učinkovitejših prevlek bo še naprej ostalo prvi pogoj za nadaljnji skok pri izkoristku plinskih turbin.

Omembe vredne izboljšave so mogoče tudi z enakomernim temperaturnim profilom pred turbino. Z izbiro materialov in hladilnega postopka je dana zgornja meja za temperaturo na površini delov. Če ne pričakujemo velikih odstopanj, lahko srednjo vrednost približamo tej dopustni zgornji meji in s tem povečamo izkoristek.

Izboljšave so mogoče tudi na periferiji plinske turbine, pri čemer v glavnem minimiramo tlačne izgube na vstopu v kompresor in tlačne izgube v izpušnem kanalu. Filtri, dušilniki zvoka in konfiguracija kanalov prav tako lahko prispevajo k izboljšavi.

Pri velikih plinskih turbinah bo v prihodnje vprašljiva tudi mehanska obdelava vedno večjih delov iz materiala, odpornega proti visokim temperaturam. Tako je treba kovati vedno večje kolute turbinskih stopenj in ulivati vedno večje segmente vodilnih lopatic. Obdelava specialnih materialov je že sama po sebi zapletena in nanašanje posebnih zaščitnih prevlek je znanost zase.

Zanimivo je tudi, da plinska turbina z danes običajnim tlačnim razmerjem, ki je optimalno za enostavni krožni proces, v kombiniranem procesu ne doseže izkoristkov, ki so mogoči s plinsko turbino pri zanj optimiranem tlačnem razmerju. Na sliki 1 so skicirane razmere pri prejšnji tehnologiji (E).

Nove plinske turbine so optimirane po enem ali drugem postopku. Vedno bolj je pri tem postalo pomembno obratovanje pri delni moči, kajti parni proces, ki sledi ekspanziji v plinski turbini, mora biti v širokem obratovalnem pasu zmožen dobavljati paro z visokimi parametri. Zaradi tega dobijo kompresorji pri vstopu po eno ali več vrst vrtljivih vodilnih lopatic.

Ne nazadnje bo vmesno hlajenje kompresorja in vmesno zgorevanje po delni ekspanziji v visokotlačnem delu turbine krožni proces močno izboljšalo. Znani so projekti, ki dosegajo izkoristke v preprostem procesu 45 odstotkov in v kombiniranem procesu nad 60 odstotkov.

Nazadnje naj bo omenjeno še načelo stopnjevanja. Zaradi zelo velikih stroškov za razvoj nove plinske turbine razvijamo en sam model plinske turbine (navadno srednje moči). Razvoj večjih in manjših plinskih turbin nato izvedemo s stopnjevanjem na podlagi teorije podobnosti. V preglednici 3 so podani pomembnejši dejavniki stopnjevanja.

Tudi modelna politika sledi določenim zakonitostim. Te lahko pridejo s trga ali pa so tako formulirane, da z eno ali dvema plinskima turbinama ene modelne vrste pokrijemo potrebo tako po najmanjši in največji kakor tudi po vsaki vmesni moči.

Searching for better materials and more effective coatings will continue to be a condition for further increases in the efficiency of gas turbines.

Improvements worth of mention are also possible with a uniform temperature profile in front of turbine. With a choice of materials and the cooling procedure, the upper limit for metal temperature on the surface of parts is given. If no large deviations in the termperature profile are expected, the mean value can be brought closer to this allowable upper limit and the efficiency thereby increased.

Improvements are also possible in the peripheral part of the gas turbine, whereby pressure loss at the inlet into the compressor and pressure loss in the exhaust channel are mainly minimised. Filters, noise dampers and the configuration of channels can also contribute to improvement.

In all large turbines, the machining of ever larger parts made from materials resistant to high temperatures will increasingly be problematic in the future. Ever larger disks of turbine stages will have to be forged and ever larger segments of leading blades (nozzles) will have to be cast. The machining of special materials is complicated and application of special protective coatings is a science in itself.

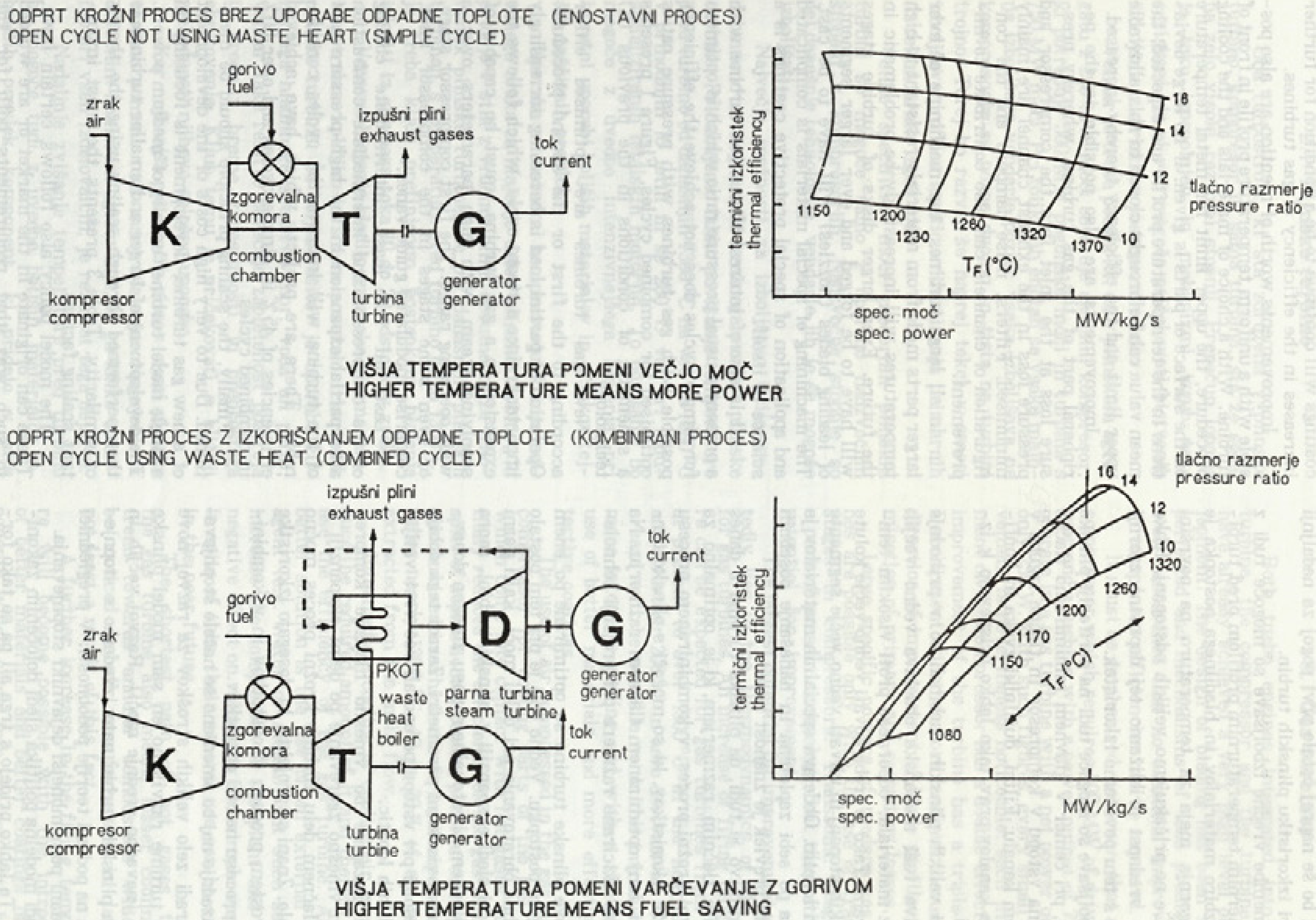
It is also of interest that a gas turbine with a presently usual pressure ratio which is optimum for simple cycles does not achieve the efficiency possible with gas turbines with pressure ratios optimised for combined cycles. Figure 1 presents a schematic of conditions in the previous (E) technology.

New gas turbines are optimised either according to the first or the second procedure. Operation at partial load is becoming increasingly important, since a steam cycle, which follows the expansion in a gas turbine, must be capable of supplying steam with high parameters over a wide operating range. The first compressor stage, or even some stages in the compressor inlet, comprise modulated guide vanes.

Last but not least, intermediate cooling of the compressor and intermediate combustion after partial expansion in the high-pressure part of the turbine will improve the cycles considerably. There are projects which have achieved efficiencies of 45% in simple cycles and over 60% in combined cycles.

Finally, the scaling principle should be mentioned. Due to very high costs of the development of a new gas turbine, development is focusing on a single model turbine (usually of medium power). The development of larger and smaller turbines is then performed through scaling using the theory of similarity. Table 3 presents the most important scaling factors.

The model policy also follows certain laws. These can originate in the market or are worded in such way that requirements both for the highest and the lowest as well as all intermediate powers are covered with one or two turbines of one model.



Sl. 1. *Optimiranje plinske turbine za enostaven in za kombiniran krožni proces*
Fig. 1. *Optimisation of a gas turbine for a simple and combined cycle*

Pregledica 3: *Stopnjevalni faktorji plinskih turbin*
Table 3: *Scaling factors for gas turbines*

Veličina/Size	Faktor/Factor 0.5	1.0	2.0
temperatura na vstopu v turbino firing temperature	1.0	1.0	1.0
tlačno razmerje pressure ratio	1.0	1.0	1.0
izkoristek efficiency	1.0	1.0	1.0
število vrtljajev number of revolutions	2.0	1.0	0.5
masni pretok mass flow	0.25	1.0	4.0
moč power	0.25	1.0	4.0
Machovo število Mach number	1.0	1.0	1.0
napetost voltage	1.0	1.0	1.0
frekvence frequencies	1.0	1.0	1.0
masa plinske turbine gas turbine mass	0.125	1.0	8.0

V preglednici 4 je podan primer za tako modelno vrsto in slika 2 kaže, da lahko izberemo za vsako zahtevano moč eno ali dve plinski turbini, ki obratujeta pri polni moči ali pa blizu nje.

Table 4 gives an example for such a model staging and Figure 2 shows that for each required power it is possible to chose one or two gas turbines which operate at full power or near it.

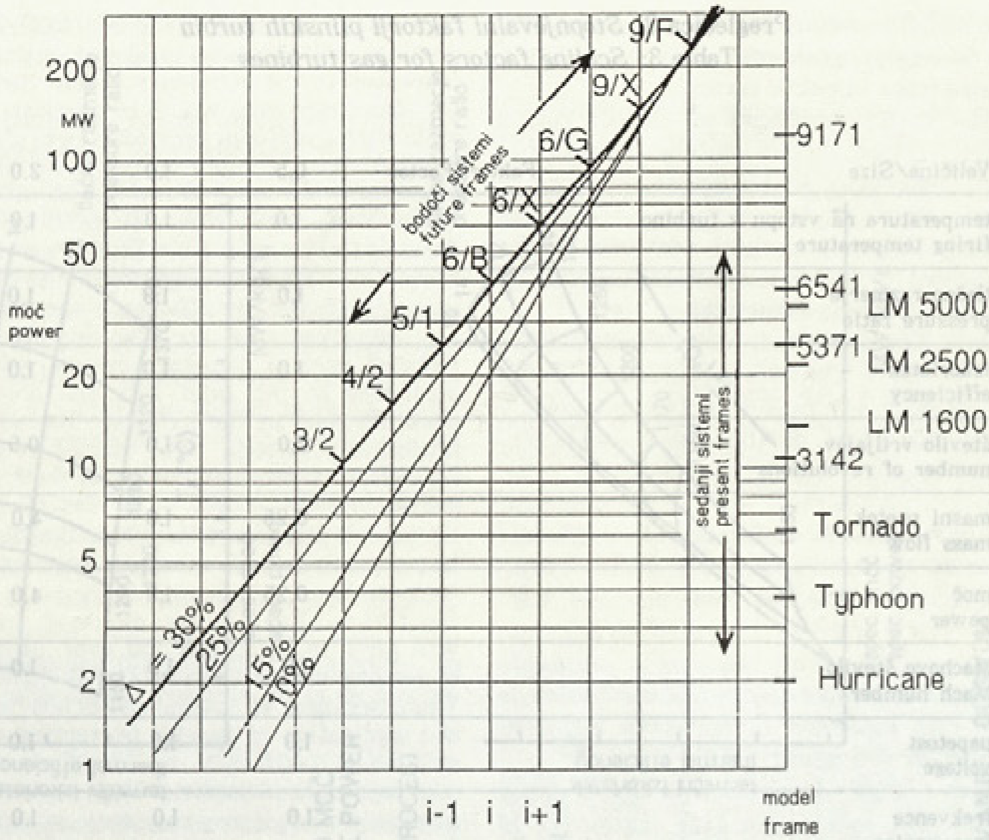
Preglednica 4: *Primer modelne vrste plinskih turbin*
Table 4: *Example of model staging for gas turbines*

$$P_{i-1} = (P_i/2)(1+\Delta)$$

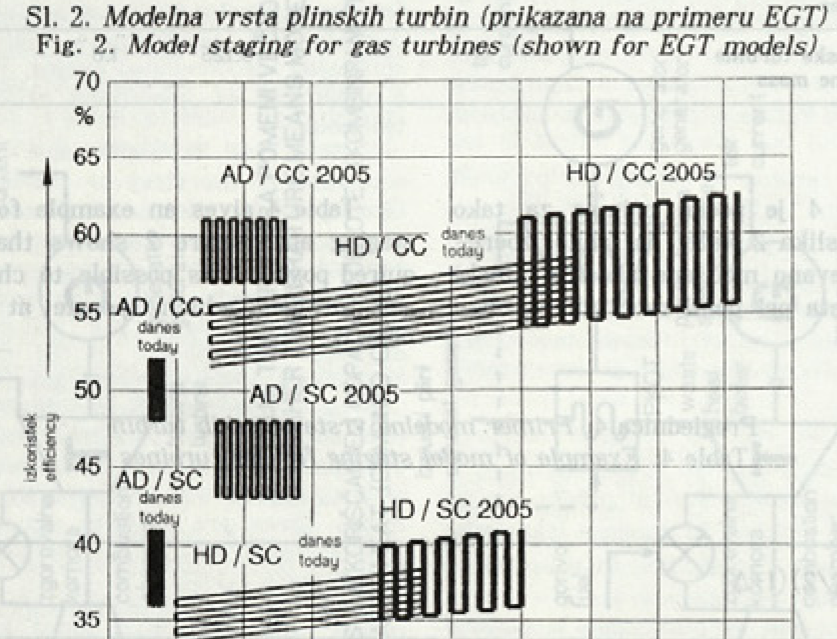
Δ	P_i	P_{i-1}	...							
0,10	225	123	68	37	20	11	6	3,5	2	...
0,15	225	129	74	42	25	14	8	5	3	...

Pri uporabi vseh teh načel in izrabi vseh omenjenih možnosti za izboljšave, je razvoj plinskih turbin do moči in izkoristkov, ki so podani na sliki 3, v naslednjih 10 letih mogoč.

In the use of all these principles and exploitation of all above-mentioned possibilities of improvement, the development of gas turbines to powers and efficiencies given in Figure 3 will be possible in the next 10 years.



Sl. 2. *Modelna vrsta plinskih turbin (prikazana na primeru EGT)*
Fig. 2. *Model staging for gas turbines (shown for EGT models)*



Sl. 3. *Napoved razvoja plinskih turbin v naslednjih 10 letih*
Fig. 3. *Forecast of development of gas turbines in the next 10 years*

2.2 Alternativni kombinirani procesi

V industriji je precej razširjena uporaba plinske turbine kot ventilatorja za obstoječi konvencionalni kotel (povezava na zračni strani).

Bolj prilagodljivo obratovanje je mogoče, če plinsko turbino zvežemo s kotlom na parni strani, kakor je to v postroju, kjer ima plinska turbina svoj PKOT, in zato lahko obratuje neodvisno od obstoječega parnega kotla.

Moč parne turbine se zmanjša na polovico in tudi izkoristek se občutno zmanjša, če namesto kondenzacijskega izvedemo protitlačni parni proces, kakor pri kombiniranih postrojih s kogeneracijo. Vendar je z uporabo toplote iz procesa mogoče povečati izkoristek postroja do 90 odstotkov. Kogeneracija torej ponuja najboljšo možnost za visoko stopnjo izrabe goriva.

Večkratno vmesno hlajenje med kompresijo in vmesno zgorevanje po vsakokratni delni ekspanziji (Ericssonov proces) omogoči pri danih vrednostih za tlačno razmerje in temperaturo pred turbino večje specifično delo in večje izkoristke, povzroči pa kompleksnost postroja in pa občutno večjo specifično ceno. Današnji trg uporabe tega postopka ne opravičuje.

Chengov proces uporablja plinsko turbino tudi kot parno turbino: vsa v PKOT pridobljena para ekspandira v turbini skupaj z zgorevalnimi plini. Tako je mogoče povečati moč za do 50 odstotkov in izkoristek za do 25 odstotkov. Pri industrializiranem letalskem motorju LM 5000 s tem postopkom povečamo moč od 33 MW na 50 MW in izkoristek od 35 odsotkov na 42 odstotkov. Upoštevati je treba, da pri tem uhaja precejšnja količina vode skupaj z izpušnimi plini v okolico in da je zato potrebna hitra priprava nove vode kot nadomestilo za izgubljeno vodo kotlovske kakovosti.

Če postavimo zgorevalno komoro ločeno od plinske turbine, se odprejo nove možnosti predvsem glede goriva. Zgorevalna komora dobi funkcijo zgorevalnega prostora in pri uporabi ustreznega prenosnika toplote postane mogoča uporaba goriv, ki sicer za plinske turbine niso primerna. Tako bi bilo vodenje dimnih plinov tlačnega kotla na premog neposredno v plinsko turbino idealna rešitev, vendar so s tem zvezani še nerešeni problemi, tako glede zamazanja lopatja in kanalov kakor tudi glede njihove korozije in erozije. Poleg tega je regulacija velikega toka dimnih plinov problematična.

Očiščen plin iz uplinjalnega postroja za premog je takoj uporaben kot gorivo za plinske turbine, čeprav ima zelo nizko kalorično vrednost. Integracija plinske turbine v uplinjalni postroj je priporočljiva, saj za uplinjanje potreben zrak lahko odvzamemo kompresorju plinske turbine.

2.2 Alternative combined cycles

The use of a gas turbine as a fan for an existing conventional boiler is quite widespread in industry (connection on the air side).

More flexible operation is possible if the gas turbine is connected with the boiler on the steam side, as happens in a plant in which the gas turbine has its own waste heat boiler and can therefore operate independently of the existing steam boiler.

The power of the gas turbine is reduced nearly by half and its efficiency also significantly if a back-pressure steam cycle is used instead of the condensation process, as is necessary in combined plants with cogeneration. But it is possible to increase the efficiency of the plant up to 90% using the heat from the cycle. Cogeneration therefore offers the best possibility of achieving the highest conversion of fuel to power.

Multiple intermediate cooling during compression and intermediate combustion after each partial expansion (Ericsson process) enables higher specific work and higher efficiencies at a given pressure ratio value and firing temperature, but it leads to complexity of the plant and a substantially higher specific price. Today's market does not justify the use of this procedure.

The Cheng process uses a gas turbine also as a steam turbine: all steam produced in the waste heat boiler expands together with combustion gases in the turbine. In this manner it is possible to increase the power output of a gas turbine by up to 50% and its efficiency by up to 25%. In an aero-derivative LM 5000, power can be increased from 33 MW to 50 MW and efficiency can be increased from 35% to 42%. It must be taken into account, however, that during this process a considerable amount of water together with exhaust gases is lost into the environment, and as a result of this intensive preparation of new water is necessary to replace the lost water of boiler quality.

If the combustion chamber is installed separately from the gas turbine, new possibilities arise above all with respect to fuel. The combustion chamber acquires the function of a combustion space and with the addition of an adequate heat exchanger it becomes possible to use fuels which are otherwise not appropriate for gas turbines. Leading flue gases of a coal-fired pressure boiler directly into the gas turbine would be an ideal solution, but it is connected with unsolved problems both with respect to build-up of ash deposits on the blades and in channels and with respect to corrosion and erosion. In addition, the regulation of a large flow of flue gases is problematic.

Purified gas from a gasification plant for coal is undoubtedly useful as a fuel for gas turbines, even though it has a very low caloric value. The integration of a gas turbine into a gassification plant is advantageous, since air needed for gassification can be taken from the compressor of the gas turbine.

Odvzet zrak se vrne v turbino skupaj z gorivom in opravi ekspanzijsko delo v njej. Če zaradi drugih vzrokov (proces uplinjanja) ne vrnemo vsega zraka v turbino, se lahko pojavi potreba po spremebi turbine.

Pri uporabi mešanice vode in amoniaka (proces po Kalini) je mogoča občutna izboljšava procesa na parni strani s tem, da toplota prehaja z enega medija na drugi pri občutno manjših temperaturnih razlikah.

Druge zanimive rešitve so mogoče z uplinjanjem biološke snovi in uporabo bio plina v plinskih turbinah. Tukaj je treba omeniti veliko prednost za ekološko stran: pri zgorevanju bio plina se sprosti približno toliko ogljikovega dioksida, kolikor ga biološka snov v fazi rasti porabi. Torej bi biološke snovi lahko prispevale k rešitvi problema tople grede.

Pri uporabi kogeneracije se pojavijo, odvisno predvsem od letnega časa, problemi z razmerjem pridobljene elektrike in toplote. Pozimi je potrebne več in poleti manj toplote, pri tem pa naj bi plinska turbina vedno obratovala pri največjem izkoristku, torej blizu polne moči. Pomoč je mogoča z uporabo sistema toplotnih premikov (STP).

Na voljo so še rekuperativni sistemi, ki so bili precej v rabi v preteklosti in so z naraščanjem tlačnega razmerja plinskih turbin izgubili pomen, saj rekuperacija lahko postane neprimerna (ali pa celo nemogoča), če se pri dani temperaturi pred turbino približa temperatura komprimiranega zraka temperaturi zgorelih plinov (ali pa jo celo preseže). Če pa rekuperativne sisteme uporabimo obenem z vmesnim hlajenjem med kompresijo, postane ta kombinacija zelo zanimiva in omogoči največje trenutno dosegljive izkoristke. V svetu teče mnogo tovrstnih projektov in uporaba takih postrojev ni več daleč.

3.3 Goriva

Velika večina kombiniranih postrojev obratuje na zemeljski plin ali na kurilno olje, čeprav je mogoče uporabiti tudi druga goriva. V večini primerov je zemeljski plin glavno, kurilno olje pa rezervno gorivo. Zato je pogled na trg goriv zanimiv.

V Evropi lahko pričakujemo do leta 2005 zvečanje porabe zemeljskega plina za 50 odstotkov. Dobava te dodatne količine še ni zagotovljena z ustreznimi pogodbami. Delež toplotnih central pri tej povečani porabi naj bi znašal 25 odstotkov.

Vprašanje po ustreznih zalogah zemeljskega plina je primerno: po današnjih tehnoloških in ekonomskih merilih zadoščajo zaloge za nadaljnjih 70 let. Pri upoštevanju ležišč, ki danes ekonomsko niso zanimiva, se povečajo zaloge na 200 let. To so obdobja, ki daleč presegajo dobo trajanja sedanjih in načrtovanih postrojev, zato vsaj to skrb lahko za zdaj izločimo.

The air taken from the compressor is returned to the turbine together with fuel and performs expansion work inside it. If for other reasons (the gasification process) not all of the air is returned to the turbine, the need to modify the turbine can arise.

In the use of a mixture of water and ammonia (Kalina cycle), substantial improvement of the process is possible on the steam side whereby heat is transferred from one medium to another with considerably smaller temperature differences.

Other interesting solutions are possible: gasification of biomasses and use of biogas in gas turbines. A large ecological advantage should be mentioned here: approximately as much carbon dioxide is released in the combustion of biogas as is used by the biomass during the growth phase. Biomasses could therefore contribute significantly to the solution of the greenhouse problem.

Depending above all on the season, problems in the ratio of produced electrical power and heat appear in the use of cogeneration. More heat is required in winter and less in summer, and the gas turbine should in addition always operate at the highest possible efficiency, i.e. near full power. The heat shifting systems (HSS) can be of assistance here.

Finally, recuperative systems are available, which were extensively used in the past and have lost their importance with the increase in pressure ratios of gas turbines, since recuperation becomes senseless (or even impossible) if at a given firing temperature the temperature of compressed air approaches the temperature of exhaust gases (or even exceeds it). But if recuperative systems are used concurrently with intermediate cooling during compression, this combination becomes very interesting and enables the highest presently possible efficiencies. Many projects of this type are being carried out around the world and the use of such plants is no longer so far off.

3.3 Fuels

A large majority of combined plants runs on natural gas or oil, even though the use of other fuels is possible. In most cases natural gas is the main fuel and oil is only the back-up fuel; an overview of the fuel market is therefore quite interesting.

A 50% increase in the use of natural gas by 2005 can be expected in Europe. The supply of this additional amount of natural gas has not yet been ensured through corresponding supply contracts. The share of thermal power plants in this increased use is expected to amount to 25%.

The question of available natural gas reserves is quite to the point: according to the present technological and economic scales, there are economically exploitable reserves for a further 70 years. Taking into account fields which are not economically interesting at present, these reserves increase to 200 years. These are time intervals which considerably exceed the life-time of existing and planned plants, so this worry can be set aside for the time being.

Zaloge premoga zadoščajo celo za 300 do 500 let. Zdaj premoga sicer še ne moremo uporabljati v plinskih turbinah, vendar nam napredki pri tehnologiji uplinjanja premoga vlivajo zaupanje v uspeh. Postroji za uplinjanje premoga z integriranimi plinskimi in parnimi turbinami pomenijo eno od možnih rešitev za naslednja stoletja, vendar ne bodo ekonomsko konkurenčni, dokler bo cena zemeljskega plina in olja ostala na današnji ravni: torej je to morebitna tehnologija prihodnosti.

Poskusi neposredne uporabe premogovega prahu v plinskih turbinah doslej niso prinesli uspeha, čeprav je bilo v tej smer v preteklih letih vloženega veliko truda. Kakor vse kaže, ima najboljše upanje za uspeh tehnologija zgorevanja premogovega prahu zunaj plinske turbine. Pri tem postopku plinska turbina nima svoje zgorevalne komore, ampak se komprimirani zrak iz plinske turbine v prenosniku toplote segreje do temperature pred turbino. Ta prenosnik toplote ima razširjeno funkcijo rekuperatorja.

Kot alternativna goriva, vendar v manjšem merilu, pridejo v upoštev še različni procesni plini in pa že omenjene biološke snovi. V nekaterih deželah tečejo pospešene raziskave za uporabo biološke snovi in prvi postroji že obratujejo.

3. 4 Emisije

Leta 1990 je 5,3 milijard ljudi »proizvedlo« 130 milijonov ton SO_2, 80 milijonov ton NO_x in 22 milijard ton CO_2. Prebivalstvo zahodne Evrope je prispevalo k tem antropogenim emisijam 16 odstotkov čeprav je tu le 8 odstotkov celotnega prebivalstva zemlje. Cenijo, da bo leta 2020 na zemlji 8,1 milijard ljudi in takratne emisije naj bi znašale »samo« 135 milijonov ton SO_2, 90 milijonov ton NO_x in 30 milijonov ton CO_2 (pregl. 5). Prebivalstva zahodne Evrope naj bi takrat bilo samo še 6 odstotkov celotnega prebivalstva in njegov delež pri antropogenih emisijah naj bi znašal samo še 10 odstotkov.

There are sufficient coal reserves for as much as 300 to 500 years. For the time being, coal cannot be used in gas turbines, but advances in the coal gasification technology have given us reason for optimism. Coal gasification plants with integrated gas and steam turbines are one of the possible solutions for the coming centuries, but they will not be economically competitive if the prices of natural gas and oil remain at their present levels; this may therefore be a possible technology of the future.

Attempts at direct use of coal dust in gas turbines have not been successful to date, even though much effort has been invested in this direction over the past years. But it seems that the technology of combustion of coal dust outside gas turbines has the best prospects for success. In this process, the gas turbine does not have its own combustion chamber; compressed air from the gas turbine is heated in the heat exchanger to the firing temperature. This heat exchanger has an extended recuperation function.

As alternative fuels, but to a lesser extent, the use of various process gases and the already mentioned biomasses can be used as fuels for gas turbines. In some countries, intensive research is being carried out in the direction of the use of biomass and the first plants are already operating.

3. 4 Emissions

In 1990, 5.3 billion people »produced« 130 million tons of SO_2, 80 million tons of NO_x and 22 billion tons of CO_2. The population of Western Europe contributed 16% to these anthropogenic emissions, even though it comprises only 8% of the Earth's entire population. It is estimated that there will be 8.1 billion people on Earth by 2020 and emissions at that time will amount to »only« 135 million tons of SO_2, 90 million tons of NO_x and 30 billion tons of CO_2 (Table 5). The population of Western Europe is expected to represent only 6% of the total population on Earth and their share of anthropogenic emissions is expected to amount to only 10%.

Preglednica 5: *Emisije škodljivih snovi*
Table 5: *Emissions of harmful substances*

Leto/Year		Svet/World		Zahodna Evropa/Western Europe
1990	prebivalstvo/population	5300	milijonov/million	8.6 %
	SO_2 emisije/emissions	130	milijonov ton/million tons	16.2 %
	NO_x emisije/emissions	80	milijonov ton/million tons	15.1 %
	CO_2 emisije/emissions	21000	milijonov ton/million tons	16.9 %
2020	prebivalstvo/population	8100	milijonov/million	6.0 %
	SO_2 emisije/emissions	135	milijonov ton/million tons	6.7 %
	NO_x emisije/emissions	90	milijonov ton/million tons	8.2 %
	CO_2 emisije/emissions	30000	milijonov ton/million tons	12.5 %

Kisle emisije se torej po zaslugi izpopolnjene tehnologije skorajda ne bodo več povečevale, medtem ko bo produkcija CO_2 zaradi povečanega števila prebivalstva kljub vsem naporom za redukcijo vendarle občutno narasla. Problem tople grede torej še zdaleč ne bo rešen.

Termične centrale Evropske zveze porabijo približno eno tretjino primarne energije, so pa trenutno odgovorne za 69 odstotkov emisij SO_2, 21 odstotkov emisij NO_x in 33 odstotkov emisij CO_2. Tehnologija redukcije žvepla in pa naraščajoča uporaba zemeljskega plina v kombiniranih postrojih bosta omogočili znižanje emisij SO_2 na 10 odstotkov (faktor 7!). Emisije NO_x bo mogoče po zaslugi dosledne uporabe že razvitih postopkov zmanjšati na polovico, medtem ko je emisije CO_2 mogoče zmanjšati samo z varčevanjem energije, boljšimi izkoristki in pa gorivi z majhnim deležem ogljika. Na tem mestu je treba spet omeniti biološke snovi, saj se obnašajo glede na emisije CO_2 skoraj nevtralno.

Da je sodelovanje prek meja na tem področju zelo pomembno, je razvidno že iz dejstva, da veter ne pozna meja. Napori ene države ne zadoščajo, prav tako ne napori ene skupnosti držav.

Skrb človeštva za okolje se povečuje in je predvsem v deželah, ki veljajo kot največje onesnaževalke, zelo velika. Zakonodaja je v preteklosti v večini dežel zaostajala za razvojem na tem področju, vendar danes skorajda ni dežele, ki ne bi imela zelo strogih predpisov glede emisij termičnih postrojev. Priznati je treba, da je varstvo okolja zelo drago in si zato marsikatera dežela doslednega varstva sploh ne more privoščiti. Le tako si lahko razložimo, da ponekod kljub vsem predpisom in zakonom vendarle nastajajo termični postroji, ki današnjih določil ne izpolnjujejo. Po drugi strani pa so nekatere dežele, ki predpisujejo strožja določila od večine in jih upravičujejo z ekonomskimi razlogi.

Graditelji termičnih postrojev in predvsem izdelovalci plinskih turbin bodo v prihodnjih letih vložili še zelo veliko truda in denarja v postopke za zgorevanje z minimalnimi emisijami NO_x in CO, da bi tako dobili rešitev, ki bi zadovoljila najstrožjo stranko (preglednica 6). Pri redukcijskih postopkih se razvoj nagiba od mokrih k suhim postopkom. Razviti in preizkušeni so že različni suhi postopki. Današnjo tehnologijo označuje emisija 50 mg/m_n^3 NO_x pri 15 odstotkih O_2 in emisija 30 mg/m_n^3 CO pri 15 odstotkih O_2. Izvedljiva je redukcija obeh vrednosti na polovico do leta 2005.

Nekatere države in dežele (Japonska, Kalifornija) že nekaj let uporabljajo katalitično redukcijo emisij NO_x. S tem postopkm skušajo zmanjšati že nastale škodljive emisije (sekundarni postopek).

Acid emissions will almost not increase thanks to improved technology, while the production of CO_2 will nevertheless increase considerably in spite of all efforts to reduce it due to an increase in the population. The greenhouse effect will therefore still be far from being solved.

Thermal power plants in the European Union use approximately one third of primary energy, but are currently responsible for 69% of SO_2 emissions, 21% of NO_x emissions, and 33% of CO_2 emissions. The technology of the reduction of sulphur and the increasing use of natural gas in combined plants will enable the reduction of SO_2 emissions to 10% (by a factor of 7!). It will be possible to reduce NO_x emissions by half thanks to the consequent use of already developed procedures, while CO_2 can only be reduced by saving energy, higher efficiency or fuels with low carbon content. Here biomasses should be mentioned again, since they are almost neutral with regard to CO_2 emissions.

The need for that cross-border cooperation in this field is very important and evident from the fact that wind knows no boundaries. The efforts of one country are not enough, nor are the efforts of one community of countries.

Responsibility for the environment is increasing and is intensive above all in those countries, which are deemed to be the greatest polluters. In the past, in many countries legislation lagged behind in this area, but today it is almost impossible to find a country which does not have very strict regulations with respect to the emissions of thermal plants. It must be admitted that environmental protection is very expensive and many countries cannot afford its consequent application. Only in this way can we explain the fact that in spite of all the regulations and laws, thermal power plants are being constructed which do not fulfil the present norms. On the other hand, certain countries prescribe stricter norms than the majority of countries and then justify them with economic reasons.

In the coming years, builders of thermal plants and above all manufacturers of gas turbines will invest much effort and funds into procedures for combustion with minimum NO_x and CO emissions in order to find a solution which will satisfy the strictest customers (Table 6). In reduction procedures, the trend is away from wet and towards dry procedures. Various dry procedures have been developed and tested. The state of the art of technology is 50 mg/m_n^3 for NO_x emissions at 15% O_2 and 30 mg/m_n^3 for CO emissions at 15% O_2. A reduction of both values by half is possible by 2005.

Certain countries and states (e.g. Japan and California) have used the catalytic reduction of NO_x emissions for a few years. With this procedure they are attempting to reduce harmful emissions which have already been produced (secondary procedure).

Preglednica 6: *Postopki za zmanjšanje emisij plinskih turbin (predvsem NO_x)*
Table 6: *Procedures for the reduction of emissions of gas turbines (above all NO_x)*

Postopek/Procedure	Prijem/Method
1. Optimiranje procesa zgorevanja Optimisation of the combustion process	temperatura plamena/flame temperature rezidenčni čas/residence time hlajenje plamena/cooling of the flame mešanica/mixture
2. Konstruktivni prijemi Design methods	stopnjevani dovod/ staged supply - goriva/of fuel - zgorevalnega zraka/ of combustion air hlajenje plamena s sekundarnim zrakom/ cooling of the flame with secondary air (dilution) predmešanje/premixing
3. Mokri postopek (vbrizgavanje vode ali pare) Wet procedure (Injection of water or steam)	hlajenje plamena z vbrizgavanjem/ cooling of the flame with injection of - vode/water - pare/steam
4. Suhi postopek/Dry procedure	kombiniranje prijemov od 1 do 3/combination of methods 1 to 3
5. Selektivna katalitična redukcija Selective catalytic reduction	katalizator v izpušnem kanalu/catalyst in the exhaust channel (popravek že nastale škode - sekundarni postopek)/ (correcting damage which has already occurred — secondary procedure)
6. Katalitično zgorevanje Catalytic combustion	katalizator v zgorevalni komori/ catalyst in the combustion chamber (preprečitev nastanka NO_x - primarni postopek)/ (prevention of the formation of NO_x - primary procedure).

Dosežene emisije NO_x so na stopnji, ki jo pričakujemo pri suhih postopkih do leta 2005. Široko uporabo katalitične redukcije pa doslej preprečuje visoka cena in kratka doba trajanja katalizatorjev.

Boljša rešitev bi bila vsekakor katalitično zgorevanje, to je postavitev takega katalizatorja v zgorevalno komoro, ki bi prinesel visoke temperature in bi preprečil nastanek škodljivih emisij (primarni postopek). Žal pa je ta postopek še daleč od komercialne uporabe, saj še ni katalizatorjev, ki bi prenesli trde pogoje v zgorevalni komori več ko nekaj sto ur.

The achieved NO_x emissions are at a level which is expected to be achieved using dry procedures by 2005. The wide use of catalytic reductions has to date been prevented by their high price and the short life-time of the catalyst.

A better solution would undoubtedly be catalytic combustion, i.e. placement of such a catalyst into the combustion chamber, which would withstand high temperatures and prevent the formation of harmful emissions (primary procedure). Unfortunately, this procedure is far from being available for commercial use since no catalysts are yet available which can withstand the conditions in the combustion chamber for more than some hundred hours.

Preglednica 7: *Pregled ekonomičnosti postopkov redukcije emisije NO_x*
Table 7: *A review of cost-efficiency of procedures for the reduction of NO_x emissions*

Sistem System	Redukcija Reduction	Investicijski stroški Investment costs	Obratovalni stroški Operating costs	Na voljo Available
vbrizgavanje vode/pare injection of water/steam	50	nizki/low	visoki 1) high 1)	od 1970 since 1970
selektivna katalizacija selective catalysing	5-20	visoki/high	zmerni do visoki moderate to high	od 1980 since 1980
suhi postopek/dry procedure	30-50	zmerni/moderate	nizki/low	od 1985 since 1985
katalitično zgorevanje catalytic combustion	< 15	visoki/high	zmerni (2) moderate (2)	še v razvoju process of development

1) Vbrizgavanje vode/pare poveča moč plinske turbine: povečana moč močno zmanjša visoke obratovalne stroške, tako da so po upoštevanju povečane moči obratovalni stroški zmerni do nizki.
The injection of water/steam increases the power of a gas turbine: increased power strongly reduces high operation costs, so that taking into account the increased power they are low to moderate.
2) Še ni gotovo. — Not yet proven.

Kakor smo že omenili, je varstvo okolja zelo drago. Preglednica 7 daje pregled postopkov za redukcijo emisij, njihove uporabnosti in investicijskih in obratovalnih stroškov.

Vbrizgavanje pare poveča tudi izkoristek plinske turbine, predvsem če je para pridobljena z odpadno toploto izpušnih plinov.

2.5 Investicijski stroški

Kombinirani postroji dajejo možnost znižati tako ceno postroja kakor tudi ceno razdeljevanja elektrike, kajti gradijo se lahko bliže porabniku in občutno ceneje kakor običajne termične centrale na premog. Specifična cena kombiniranega postroja znaša npr. 1000 DEM/kW na ključ, kar je manj od polovice cene za enako veliko toplotno centralo na premog in manj ko ena tretjina postroja z integriranim uplinjanjem premoga (preglednica 8). Gradnja manjših enot je sicer specifično dražja vendar v primeru kombiniranih postrojev manj kakor pri toplotnih centralah na premog.

As mentioned, environmental protection is very expensive. Table 7 gives an overview over the procedures for the reduction of emissions, their applicability and investment and operating costs.

The injection of steam also incrases the efficiency of gas turbine, especially if the steam is produced with the waste heat of exhaust gases.

2.5 Investment costs

Combined plants offer the possibility of reducing both the price of plants and the price of the distribution of electric power, since they built nearer to customers and can be less expensive than conventional coal-fired thermal power plants. The specific price of a combined plant amounts to e.g. DM 1,000/kW (according to the turn-key principle), which is less than one half of the price for a coal-fired power plant of the same size and less than one third of a plant with integrated gassification of coal (table 8). The construction of small units is specifically more expensive, but in the case of combined plants this is lesser than in coal-fired thermal power plants.

Preglednica 8: *Investicijski stroški za energetske postroje*

Table 8: *Investment costs for power plants*

Proces/Process	Specifična cena DEM/kW/Specific price in DEM/kW
preprosti proces s plinsko turbino simple process with a gas turbine	600
kombinirani proces s plinsko in parno turbino combined process with a gas and a steam turbine	1000
toplotna centrala na premog coal-fired thermal power plant	2400
integrirano uplinjanje premoga in kombinirani proces integrated gassification of coal and a combined process	3500

V preglednici 8 navedene cene so seveda samo informativne in temeljijo na industrijskih standardih in predpostavljajo tipizirano gradnjo. Možnost porazdelitve moči na dva do štiri agregate omogoča po eni strani izpolnitev omenjenih standardov in po drugi strani doseganje zelo visokih stopenj razpoložljivosti vsaj delne moči.

Evropska konkurenca, velika produktivnost in zmanjšani stroški proizvodnje omogočajo danes cenejše ponudbe za kombinirane postroje kakor še pred dvema letoma.

The prices listed in Table 8 are naturally only for informative purposes; they are based on industrial standards and assume standardised design. The possibility of the distribution of power to two to four aggregates enables on one hand compliance with the above-mentioned, and on the other the achieving of very high degrees of availability of at least partial power output.

Competition in Europe, high productivity and reduced production costs have now enabled cheaper tenders for combined plants than were possible two years ago.

Kombinirani postroji so zelo občutljivi na ceno zelo kakovostnega goriva. Vendar je upanje utemeljeno, da bo cena goriva ostala stabilna, saj:

— so zaloge zemeljskega plina velike,

— je število proizvajalcev in dobaviteljev veliko,

— je politika oblikovanja cen energije zapletena in povezana za vse vrste goriva,

— močno razvejana mreža plinovodov je na voljo in jo je treba le vzdrževati (Nemčija npr. ima 237000 km plinovodov).

2.6 Politika

Skrb za stalno oskrbo z električno energijo, želja po neodvisnosti od uvoženih goriv in ohranitev delovnih mest je v mnogih deželah pripeljala tako do državnih monopolov kakor tudi do subvencij, ki so spremenile stanje na trgu, deloma izločile konkurenco in povzročile zelo različne cene. Tako je npr. v Nemčiji cena ene kWh zaradi uporabe domačega premoga, zaradi povečanega varstva okolja, dolgih postopkov za dovoljenje gradnje, razdelilne mreže, ki je položena deloma v zemlji, in zaradi visoke obdavčitve približno za 0,06 DEM bolj obremenjena kakor v sosednji Franciji.

Politiki že pletejo nove mreže v obliki obdavčitve emisij CO_2, predpisov za uporabo toplote, kakor tudi strožjih predpisov glede emisij (»TA-Luft«). Če teh usmeritev ne bo mogoče uskladiti vsaj znotraj Evropske zveze, bo znakaženje trga postalo še večje in konkurenca bo popolnoma izločena.

Prihodnji predpisi nacionalne in evropske politike pomenijo veliko tveganje za lastnike energetskih postrojev. Kombinirani postroji so še najmanj v nevarnosti, saj manj obremenjujejo okolje, zahtevajo manjše investicije in imajo krajšo amortizacijsko dobo. So tudi idealno primerni za kogeneracijo, vendar niso zavarovani proti morebitnim neugodnim spremembam.

Nedvomno bo namera Evropske zveze ločiti pridobivanje električne energije od njenega razdeljevanja, kakor tudi dovoliti dostop do razdeljevalne mreže tretjim — če bo uresničena — zelo poostrila konkurenco med proizvajalci električne energije.

Za domačega proizvajalca električne energije bo s tem omogočena dobava cenenega goriva in dana spodbuda, pridobiti več električne energije, kakor je sam potrebuje, če jo bo le lahko ugodno prodal.

Combined plants, however, are very sensitive to the price of high-quality fuel. But hope that the price of fuel will remain stable is justified, since

— the reserves of natural gas are large,

— the number of explorers and suppliers is high,

— the pricing policy for energy is complex and interconnected for all types of fuels,

— a strongly branched network of gas supply pipelines is available and must only be maintained (Germany, e.g. has 237,000 km of pipelines).

2.6 Policy

The responsibility for an uninterrupted supply of electric power, the desire for independence from imported fuels and preservation of workplaces led to state monopolies and subsidies in many countries, which has deformed the situation in the market, partly eliminated competition and caused widely varying prices. In Germany, e.g. one kWh has approximately DM 0.06 more costs attached than in the neighbouring France, due to the use of very expensive domestic coal, intensive environmentral protection, long procedures required to obtain permits for construction, a distribution network which is laid partly in the ground and high taxes.

Politicians are already weaving new webs in the form of taxation of CO_2 emissions, regulations for the use of heat, as well as stricter regulations with regard to emissions (»TA-Luft«). If these trends cannot be coordinated at least within the European Union, the deformation of the market will become even greater and competition will be completely eliminated.

Future regulations in national and European politics mean a large risk for the owners of power plants. Combined plants are the least threatened, since they pollute the environment less, demand lower investments and have a shorter depreciation period, and are ideally suited for cogeneration; however, they are not immune to possible unfavourable changes.

The intention of the EU to separate the production of electric power from its distribution as well as to allow access to the distribution network to third parties will undoubtedly - if it is implemented - make the competitive situation between producers of electric power stiffer.

However, this will provide domestic producers of electric power with a supply of cheap fuel and encourage them to produce more electric power than they need themselves, if only they can sell it under favourable conditions.

3 SKLEP

Kombinirani postroji s plinskimi in parnimi turbinami dajejo najbolj gotovo oskrbo z električno energijo in obenem omogočajo tako ohranjanje dela goriva za kasnejšo uporabo kakor tudi intenzivno varstvo okolja. Stalen razvoj jih je danes pripeljal do razpoložljivosti nad 96 odstotkov in omogočil izkoristke do 58 odstotkov.

Nadaljnji razvoj v naslednjih 10 letih dovoljuje pričakovanje izkoristkov nad 60 odstotkov in stopnjo izrabe goriva pri kogeneraciji blizu 92 odstotkov. Pri tem bo dosegla plinska turbina v težki izvedbi v preprostem procesu izkoristke več ko 40 odstotkov in v izvedbi z vmesnim hlajenjem ter vmesnim zgorevanjem več ko 45 odstotkov. Industrializirani letalski motorji bodo dosegli v enostavnem procesu še dva ali tri odstotke več.

Pri pogonu plinskih turbin s kurilnim oljem, predvsem pa z zemeljskim plinom, bodo emisije dušikovih oksidov in ogljikovega monoksida občutno nižje. Delež nezgorelih ogljikovodikov bo nepomembno majhen in žveplove spojine po zaslugi goriva (predvsem plina) bodo zanemarljive. Tudi emisije posameznih delcev bodo minimalne.

Kompleksni procesi s plinskimi in parnimi turbinami bodo zaradi nizkih cen goriva za zdaj ostali še teorija. Njihov razvoj bo tekel naprej, tako da bodo na voljo v primeru ponovne svetovne energetske krize. Postopna uveljavitev kompleksnih procesov se bo začela šele v novem stoletju, razen če jo bodo nepredvideni dogodki pospešili.

Krmiljenje, zanesljivost in ravnanje s postrojem govorijo zdaj še proti kompleksnim postrojem. Izziv bi bil jih tako izpopolniti, da bodo v prihodnje prav tako zanesljivi in prav tako nezahtevni v pogonu, kakor so današnji preprostejši postroji.

Med novimi gradnjami so dosegli kombinirani postroji že občuten delež. Ta se bo še naprej zvečeval in bo na pragu novega stoletja dosegel 50 odstotkov. Zvečanje na več ko 60 odstotkov v prvih letih prihodnjega stoletja je uresničljivo.

Zemeljski plin in kurilno olje bosta še dolgo na voljo kot optimalni gorivi za kombinirane postroje. Ker večina plinskih turbin lahko obratuje na plin in tudi na kurilno olje in ker je konkurenca dobaviteljev obeh goriv precejšnja, upravičeno predpostavljamo, da bo cena ostala stabilna, razen če bi se svetovnopolitične razmere nenadoma spremenile.

3 CONCLUSION

Combined plants with gas and steam turbines offer the safest supply of electric power and at the same time enable the preservation of fuel for later use as well as intensive environmental protection. Constant development has now enabled availability exceeding 96 % and efficiencies of up to 58 %.

Further development in the next 10 years will justify the expectation of efficiencies above 60 % and a degree of fuel efficiency in cogeneration near 92 %. Gas turbines in the heavy duty version will achieve efficiencies exceeding 40 % in a simple cycle and over 45 % in the version with intermediate cooling and intermediate combustion. Industrialised aircraft engines will achieve a further 2 or 3 % more in the simple cycle.

For gas turbines burning oil, but above all these burning gas, emissions of nitrogen oxides and carbon monoxide will be substantially lower. The levels of unburnt hydrocarbons will be insignificantly low and those of sulphur compounds will be negligible thanks to fuels (predominantly gas). Particle emissions will also be minimal.

Complex processes with gas and steam turbines will remain theoretical due to low fuel prices. Their development shall continue, so that they will be available in the case of repeated world energy crisis. A gradual enforcement of complex processes will begin in the next century, unless it is hastened by unexpected events.

Control, reliability and operation of plants speak against complex plants for the time being. It will, however, be a challenge to perfect their development to such and extent that they will be just as reliable and simple to operate in the future as today's simpler plants.

Combined plants have achieved a notable share among newly constructed plants. This development will continue to increase and will achieve 50 % on the eve of the next century. It is realistic to expect an increase to over 60 % in the first years of the coming century.

In the future natural gas and oil will be for long available as optimum fuels for combined plants. Since the majority of gas turbines can run both on gas and oil, and since the competition among suppliers of both fuels is considerable, it is reasonable to assume that the prices will remain stable unless the political situation in the world suddenly changes.

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