Part 6

ADVANCED TECHNOLOGIES AND POWER INSTALLATIONS FOR THERMAL AND ELECTRIC ENERGY GENERATION

6.2. Gas turbine and combined-cycle units

6.2.1. Prospects of application of gas-turbine and combined-cycle units in thermal engineering

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Development of gas turbine (GT) and combined cycle (CC) units. Fuel balance of thermal power plants of the Russian Federation with the prevailing share of natural gas (more than 70 %) should predetermine a wide application of the combined-cycle technology for power generation. This applies especially new construction in regions, provided with natural gas. In this case it's possible to construct the most efficient binary CC, where all heat is supplied together with fuel to the GT unit (GTU) and the steam is generated and superheated using heat from the GT exhaust gases. High efficiency of binary CC plants is achieved under moderate steam parameters and a simple flow cycle of the steam turbine plant.

Considerable economy of fuel and capital costs can be also obtained by building-up of the operating power units with gas turbines [1, 2].

The key issue of CC technology application in power industry is availability of efficient and reliable gas turbines. The leading power machinery manufactures ("General Electric", "Mitsubishi Heavy Industries", "Alstom", "Siemens") have developed gas turbines being as reliable as steam turbines or even higher, with lower unit cost and operational expenses. High reliability and efficiency resulted from application of scientific and construction studies in gas dynamics, heat and mass transfer, combustion, mechanics and construction strength, material science, metallurgy and metal working [3—5].

The following is characteristic for GTUs, manufactured nowadays:

- mono-crystal blades of the first stage and sometimes of the second stage with thermal protection and anticorrosive coating and blades with directed crystallization of the following stages;
- air (and in the long term — steam) cooling of the blades;
- rotary directing apparatus in an input or in the several first stages of the compressor;
- low toxic "dry" combustion chambers burning preliminary prepared fuel/air mixture or equipped with multi staged fuel burning.

Development of GTUs resulted in considerable increase in efficiency of CC units. Currently their efficiency in the Western countries has already reached 58,5 %, and reliability is the same as of traditional steam units and even higher.

Further progress in development of GTU is connected with achievements in the field of development of new materials and blade cooling systems. Application of steam or water for their cooling will provide a further increase in initial temperature and consequent efficiency increase.

At early stages of GTU development much attention was paid to perfection of their cycle with the help of intermediate air cooling under compression, intermediate heating of gases at their expansion in the gas turbine, exhaust heat regeneration for compressed air heating. In particular, a domestic GT-100 with a capacity of 100 MW, where intermediate air cooling at compression and intermediate gas heating are applied, was constructed and is under operation since 1970. This unit was competitive with the world samples. Besides, there were designed and are under further development the gas/steam units, in which water steam, generated by exhaust heat, is additionally used. It is mixed with combustion products in the combustion chamber.

Advantages of CCUs in comparison with steam turbines are as follows:

- high economical efficiency and respectively low harmful impact on the environment;
- low capital costs;
- shorter construction period and possibility of stage-by-stage commissioning of power units (the first stage is GTU and the second- CCU).

A task of the domestic power gas turbine machinery construction is mastering of initial gas temperatures of 1100 … 1200°C and higher aimed at increase in GT efficiency up to 33 … 37 %.

GTU tests with capacity of 110 MW of GTE-110 type were started in 1999. GTE-110 was designed by a scientific industrial unit (SIU) "Mashproekt" in Nikolayev; its manufacture was mastered by a scientific industrial unit (SIU) "Saturn" (Rybinsk). Serial production of GTE-110 in SIU "Saturn" started in 2007. The first two GTUs were supplied to Ivanovo State District Power Plant for operation within a CCU with a capacity of 325 MW. The third serial GTU will operate as a build-up unit of 300 MW at Novomichurinsk State District Power Plant #24.

Currently almost all manufacturers of aviation engines have conversion programs and develop engines for industrial application. Samara scientific technical complex (STC) "Engines NK" is already manufacturing a power GTU of NK-37 type with a capacity of 25 MW and is designing its next modification of 30 MW with 37% efficiency. Machinery manufacturing enterprise "Salute" (Moscow) and Joint-Stock Company "Energoavia" (Moscow) produce GTU with capacity of 20 MW and efficiency of 31÷33 %.

Modernization of thermal power plants. The most efficient way of implementation of a CC technology for power generation is conversion of the existing thermal power plants with steam turbines to CC ones by building-up with gas turbines [1, 2].

Efficiency of a built-up power unit (CCU) depends on three parameters — gas turbine efficiency, steam turbine efficiency and a share of heat, supplied with fuel to the GTU in the total quantity of fuel heat used in the CCU. Table 6.3. shows influence of each of the above mentioned parameters at a CC efficiency.

As it could be seen from Tab. 6.3, a binary CC is more efficient under equal GT efficiencies even having lower efficiency of a ST. However, lower capital costs for modernization of the existing power units can have crucial importance compared to a new construction of binary CC units.

Table 6.3. **Influence of a binary factor at the steam turbine unit efficiency**

A share of heat, supplied to the GTU	GTU efficiency	STU efficiency	CCU efficiency
1	0,32	0,30	0,52
1	0,36	0,32	0,57
1	0,36	0,36	0,59
1	0,38	0,38	0,61
0,3	0,32	0,41	0,47
0,4	0,32	0,41	0,49
0,3	0,36	0,41	0,48
0,4	0,36	0,41	0,50
0,3	0,36	0,45	0,51
0,4	0,36	0,45	0,53

Considerable quantity of various gas-turbine build-up schemes complicated a choice of an optimal option. However, it is possible to narrow the considered schemes using unconditional criteria, based on technical restrictions. The above criteria are as follows:

1) a possibility of a CCU scheme implementation under specific conditions of the considered power plant;

2) a thermal technical efficiency of the scheme;

3) necessity and duration of the main equipment reconstruction;

4) operational flexibility and reliability of the modernized unit.

The first criterion is, first of all, connected with the availability of space in the main building and at the power plant territory for location of GT-built-up equipment. In some cases this criterion may become critical.

The second criterion refers to the efficiency of the power unit modernization, determined by saving of specific fuel consumption under different operational conditions (for example, at considerable fluctuations of ambient temperature) and at variable operating modes (for example, at partial loadings, with a various number of gas turbines).

Meaning of the third criterion depends on available reserve power in the power system. In case this reserve power is enough and shut-down of the power unit for its reconstruction will not cause a power supply failure, then choice of the GTU-building-up scheme becomes only of a financial and economic issue. In case, there’s a lack of the reserve and its shortage can’t be covered by inter-system connections, then even a high-effective option, requiring more time for its implementation that a scheduled maintenance period, can’t be recommended for use.

Application of the fourth criterion is connected, first of all, with a power plant operating mode within a power supply system (maneuverable or base mode) and requirements for reliability of the main and auxiliary equipment (for example, a requirement for independent STU operation at a switched-off GTU).

Depending on connection between the gas turbine and the steam power unit, schemes of GTU-build-up can be divided into parallel and sequential ones. In parallel schemes heat-recovery steam generators (HRSG) are used. A HRSG generates steam of one or two pressures, entering a certain point of the steam turbine cycle, or a condensate, feed water or heating system water are heated. Some of these schemes are presented in Fig. 6.6.

Sequential scheme is one with discharge of GTU exhaust gases into burners of a power boiler. It is shown in Fig. 6.7.

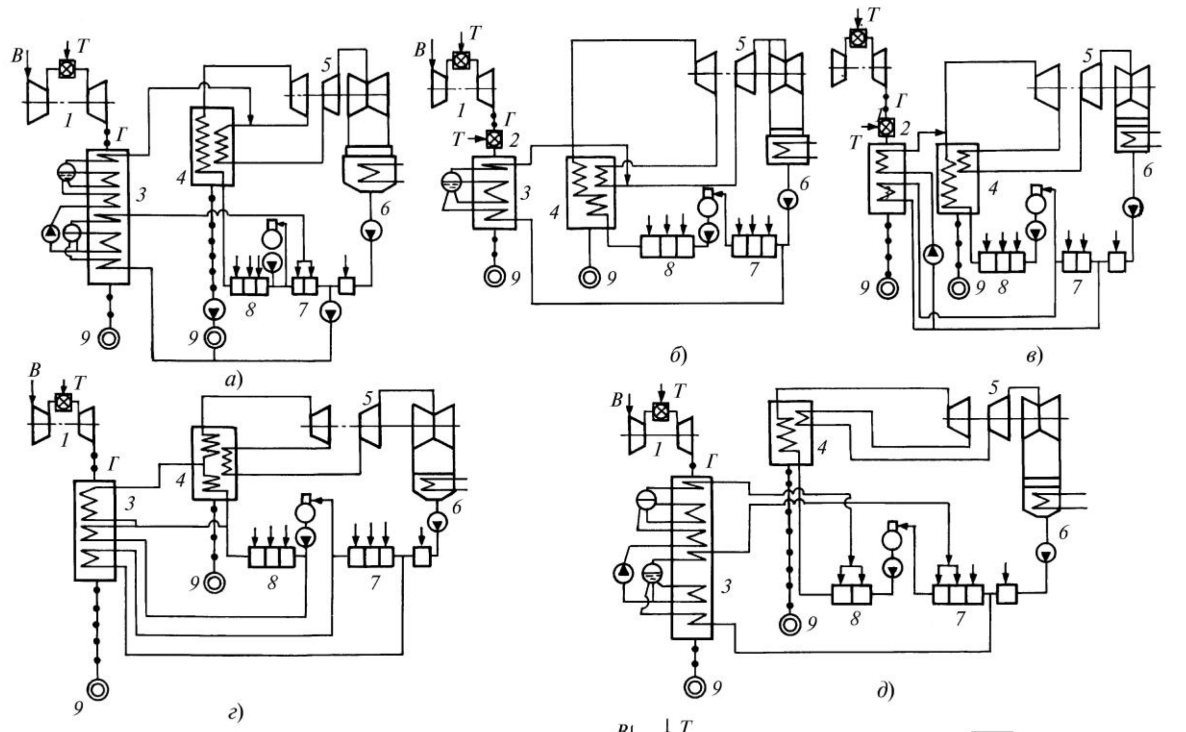
There are also combined schemes, in which GTU exhaust gases are partially cooled in an independent gas-water heat exchanger, and then directed to the boiler burners.

Comparison of the described GTU build-up options, including application of GTE-110 gas turbine of SIU “Mashproekt” for the initial steam power unit of 300 MW is presented in Tab. 6.4.

Among the described above schemes, the most economically efficient is the GT-built-up one with exhaust discharge to the power boiler.

Table 6.4**. Relative efficiency of CCUs with different types of GT-build-up**

Type of GT build-up	Fuel economy compared to steam-power unit, %
Scheme with GT exhaust discharge in a furnace of the power boiler	10,4
Parallel scheme with generation of slightly superheated steam and its supply to the superheater of built- up boiler + heating of a feed water and main condensate with GT exhaust	8,5
Parallel scheme with the feed water heating up to 330°C and main condensate heating with GT exhaust	7,2
Parallel scheme with steam generation of cold reheat parameters and further supply to the reheater of a power boiler + main condensate heating with GT exhaust	6,0
Parallel scheme with superheated steam generation and its further supply to the steam turbine + main condensate heating with GT exhaust	5,8
Parallel scheme with steam generation with hot superheating parameters and its supply to the steam turbine	5,2
Parallel scheme with the feed water heating up to the nominal value after high pressure heater + heating of the main condensate with GT exhaust	3,5



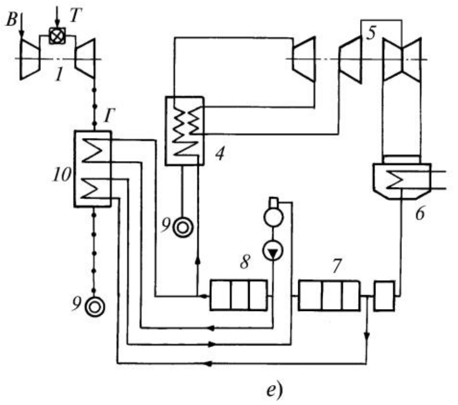


Fig. 6.6. Parallel schemes of gas turbine build -up:
а — steam supply to the cold reheat piping; *б* — steam supply to the hot reheat piping; *в* — steam supply to the raw steam piping; *г* — steam supply to the intermediate point of a boiler steam path; *д* —substituting of steam from a steam turbine regeneration system with steam from a HRSG; *е* — installation of gas-water heaters (GWH) for heating of condensate and feed water instead of a steam turbine regeneration system;
1 — gas turbine; *2* — burners of a HRSG;
3 — HRSC; *4* — boiler of a build-up unit;
5 — steam turbine; *6* — condenser; *7, 8* — low and high pressure heaters; *9* — stack; *10* — GWH of low and high pressure;
Т — fuel; *В* — air; *Г*— gases

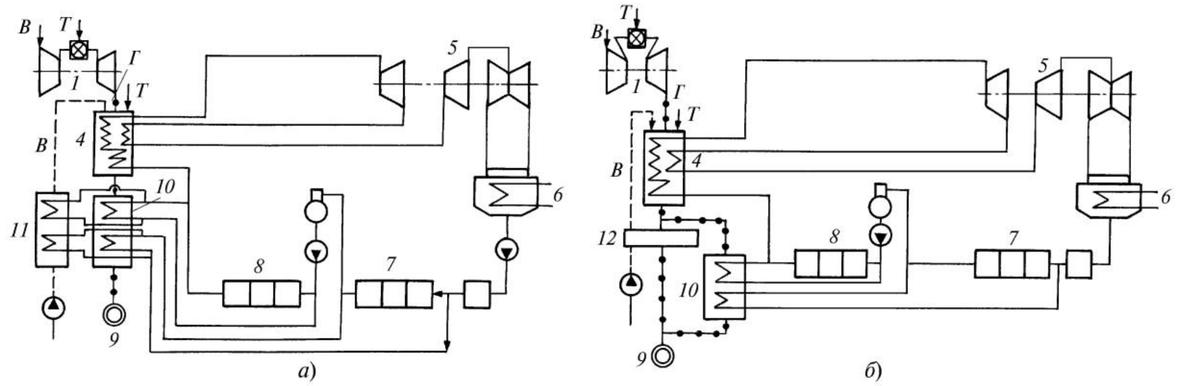


Fig. 6.7. Discharge schemes of gas turbine build-up:
а — with gas discharge from the gas turbine to the boiler and with blow air heating in a radiator; *б* — with gas discharge from the gas turbine to the boiler and with heating of blow air with exhaust gases; *1—10* — the same as in Fig. 6.6; *11* — radiators of blow air; *12* —air heater

Table 6.5. **Technical and economic characteristics of GT units with discharge scheme**

Characteristics	Power unit				
	300 MW capacity		800 MW capacity		
GTU type	GTE-110		GTE-110		GTE-160
GTU quantity	1		2	3	2
Raw steam consumed by the turbine, t/h	930	800	2000		
Secondary steam consumption, t/h	817	712,6	1909,6		
GTU capacity, MW	107,5	107,5	227	340,5	317,2
Steam turbine capacity, MW	325,9	287,8	759,8	769,7	765,8
Power unit capacity (gross), MW	433,4	395,3	986,8	1110,2	1083
Power unit capacity (net), MW	423,6	385,5	974,6	1097	1070,7
Power unit efficiency (net), %	44,51	44,78	45,9	48,0	47,87
Fuel saving compared to a steam turbine unit, %	11,6	12,2	9,5	13,5	13,1
Environmental characteristics at oil combustion:					
specific NO_x emissions, kg/(MW·h)	0,57	—	—	—	—
reduction compared to steam turbine units, %	35	—	—	—	—
specific $S0_2$ emissions, kg/(MW-h)	7,9	—	—	—	—
reduction compared to steam turbine units, %	25	—	—	—	—

Table 6.5 summarizes technical and economic characteristics of 300 and 800 MW power units, built-up with GT according to the discharge scheme.

Gas-turbine build-up of coal-fired power units. Parallel GTU-build-up schemes can be used for coal-fired power units without solving additional problems, connected with coal dust combustion in the GTU exhaust. However, problems with steam turbine unit and partial loading of the built-up unit may occur.

Issues of GTU application for build-up of coal-fired boilers, using a discharge scheme, were not thoroughly studied in the national thermal engineering. The first attempt of a boiler design for the coal-fired unit of 300 MW as well as GTU of GTE-110 type was undertaken by VTI and SibVTI in 1993. The results of their studies are described below. Capacity of CCU in this option made about 500 MW.

Use of the discharge scheme of the GT-build-up is connected with a problem of coal dust combustion in GTU exhaust. However, its solution is proved by a wide application of the discharge scheme in GT-build-up at coal-fired thermal power plants in Germany.

National experience which could be used for this purpose is very limited. However, experience in construction and operation of boilers burning Kansko-Achinsky coal with direct blowing of coal dust (for example P-67 of the 800 MW unit) testifies the absence of problems on coal dust burning out in case of supply of drying and recirculation gases into burners. Besides, there are positive results of bench studies, showing that decrease in oxygen worsens conditions of a flame firing and lowers an intensity of burning, but is was noted that the flame is steady enough. Professor V.I. Babiy (VTI) established that it is important to intensify a mass exchange at the firing and burning stages, especially, when using GTU exhaust gases as secondary air.

The following measures can be introduced to intensify fuel burning-out:

- coal dust grinding using, in particular, two-stage separator of SibVTI design;
- application of direct-flow burners with peripheral and dispersed supply of the air and fuel mix, as well as with the central blowing of the secondary air. Such burners have high firing parameters and efficient mixing of air and fuel mix with the secondary air;
- application of furnaces with turbulent aerodynamics (with tangential layout of direct-flow burners).

For the unit of 300 MW the boiler was designed, during the operation of which an effective burning of Kansko-Achinsky coal and low emissions of pollutants are provided. Coal combustion is arranged, using direct blowing, which favorably proved itself at P-67 boiler for the unit of 800 MW and for E-500 boiler.

The technology of staged combustion of coal in GTU exhaust was designed for reduction of NOx emissions.

Technical and economic characteristics of the unit at the ambient temperature +15°C and a temperature of cooling water +12 °C in the independent (steam power unit) and combined (CCU) modes are summarized in Tab. 6.6.

Table 6.6. **Technical and economic characteristics of 300 MW power unit in the independent and combined modes**

Characteristics	Modes	
	STU	CCU
Raw steam consumption, t/h	1000	1000
Raw steam temperature, °C	540	540
Steam reheat temperature, °C	539	541
Steam flow through the reheater, t/h	797,5	833,8
Water flow through the high pressure gas/water heater, t/h	—	200
Water flow through the low pressure gas/water heater, t/h	—	1500
Fuel consumption, t/h	193,79	171,475
Exhaust temperature, °C	152	159
Boil efficiency (gross), %	92,0	90,85
Steam turbine capacity, MW	338,2	355,05
Gas turbine capacity, MW	—	107,5
Capacity of the unit (gross), MW	338,2	462,55
Efficiency of the unit (gross), %	42,23	47,77
Capacity of the unit (net), MW	317,9	442,35
Efficiency of the unit (net), %	39,69	46,69

Table 6.7. **Basic characteristics of ST and CC units operating in the independent and combined modes**

Characteristics	Modes	
	STU	CCU
Steam consumption, t/h	1000	1000
Fuel consumption, t/h ($Q_{l.w}$ = 14 863,9 kJ/kg)	190,854	168,649
Air-to-fuel ratio in the furnace	1,2	1,2
Flue gas flow, m^3/t	1 100 880	1 299 960
Natural gas consumption by GTU, kg/s ($Q_{l.w}$ = 49 180 kJ/kg)	—	10,49
Air-to-fuel ratio after GT	—	3,37
Gas flow after GT, kg/s	—	362,3
Power unit capacity (gross), MW	339,0	458,5
NO_x emissions from the boiler, kg/h	247,7	292,5
Specific NO_x emissions:		
kg/(MW·h)	0,73	0,64
g/MJ	0,087	0,067
Dust emissions, kg/h	55,04	65,0
Specific dust emissions:		
kg/(MW·h)	0,16	0,14
g/MJ	0,019	0,015

Environmental characteristics. Staged coal dust combustion in the independent mode of the boiler operation should provide a standard concentration of nitrogen oxides — 225 mg/m^3. Operation in the combined mode, when GT exhaust is used instead of secondary air, results in NO_x emission reduction or simplification of the burning process, keeping the standard concentrations of NO_x.

Operational experience of two discharge CCU-250 shows that switch from the independent mode to the combined one results in NO_x reduction by about 35%.

Similar considerations can be referred to ash emissions too. In case when a dust cleaning system is designed to provide the standard rate concentration of ash in exhaust gases (50 mg/m^3) for the independent mode, then in the combined mode it will be decreased, firstly, due to lowering the coal consumption (by 12%) and, secondary, due to increase in flue gas volume (by 18 %).

Comparison of the independent and combined modes is given in Tab. 6.7. at the conservative approach, i.e. it is accepted that in both modes concentrations of NO_x and dust are the same (standard).

Thus, even at the conservative approach, in CCU modes it is expected a decrease in specific NO_x emissions by12,3 % in reference to the generated electric energy, and to the fuel consumption — by 23 %. Specific emissions are thus reduced:

- in reference to the developed electric energy — by 12,5 %;
- in reference to the burned fuel — by 21 %.

It should be noted, that if filtering equipment is selected for the combined operation mode, then its capital costs are considerably cut.