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On the Goliński-Jesionek multistage combined air/steam systems with external combustion

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Abstract

In the paper a brief review of an air/steam set of thermodynamic cycles dedicated for energy production is presented. The main aim of this work is show to the Goliński-Jesionek multistage combined air/steam plants which improve efficiency. For this purpose, systems are first studied and secondly new concept is presented.

Keywords: Binary cycles; Combined cycles; External combustion; Air/steam power plants

1 Introduction

Gas turbines [1] are becoming increasingly important in new energy investments, especially related with distributed electric power generation. It belongs to rather hierarchic [2] power systems which are included into turbine installations:

- combined cycle gas turbine (CCGT),
- combined dual-fuel,
- with total coal gasification,
- with partially coal gasification,
- with pressured coal combustion in fluidized bed boilers,
- with pressured coal combustion in pulverized-fuel boilers,
- direct coal combustion in gas turbines,

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- gas-steam with fuel cells,
- combined air/steam.

Besides typical gas/steam systems (CCGT) the rest of the mentioned cases of energy technologies are in the early stages of scientific and technical research.

In last few years two Professors of Wrocław University of Technology – Józef A. Goliński and Krzysztof J. Jesionek – were working on concepts of air/steam power station system. Józef Antoni Goliński has spend his youth and obtained a high school education before Second World War. Krzysztof Jan Jesionek was born in 1944 so he had the occasion – from the beginig – to live and get complete education in postwar Poland. Even before war Professor Goliński had worked for 8 years in machinery industry and he managed to complete his higher education in the country and abroad while several postwar years in the field of machine design. He had also occasion to refer to the field of gas turbine and mechanic vibrations in Canada. Instead Professor Jesionek graduated Wrocław Unversity of Technology. He completed an internship in Department of Steam and Gas Turbines in Moscow Power Engineering Institute. He is expert in the field of heat technique and power machinery and devices.

Although both Professors have worked in different Faculties of University (Environmental Engineering and Mechanical and Power Engineering), for several years they had worked in the same building (B-1, Old Metallurgical) and moreone – in adjacent rooms. In this period of time while one of meeting Professor Józef Goliński suggested Professor Jesionek to come back to the idea of air turbine gas system which he was working on in the first half of the 50's of the last century in the team of D.L. Mordell (while intership in McGill University in Canada). Over 10-years cooperation (to the moment of Professor Józef Goliński death on 18th of February 2011) effected in series of common national and foreign publications which were culminating in the publication of two books. Professors drew attention to the possibility of linking air turbines systems and steam installations:

- producing electric energy and heat,
- gasification of coal.

Especially the last one, required a power supply of both jets steam and air (or oxygen), is dedicated to linking it with air/steam power plant because necessary media can then be downloaded directly from the respective discounts. Due to the fact that it's very rare to see these subjects positions in world literature, it is important to point up leading effort of native technic idea in development of this field.

2 Hierarchic system and heat regeneration

In binary power station there are used two working fluids. Well known examples are common in combined cycle gas turbine (Figs. 1 and 2). The basic cycle contains (Fig. 1): gas turbine (T) , compressor (C), combustion chamber (CC), electric generator (GE), heat recovery steam generator (HRSG), steam turbine (ST), pump, condenser, economizer, evaporator, superheater, deaerator.

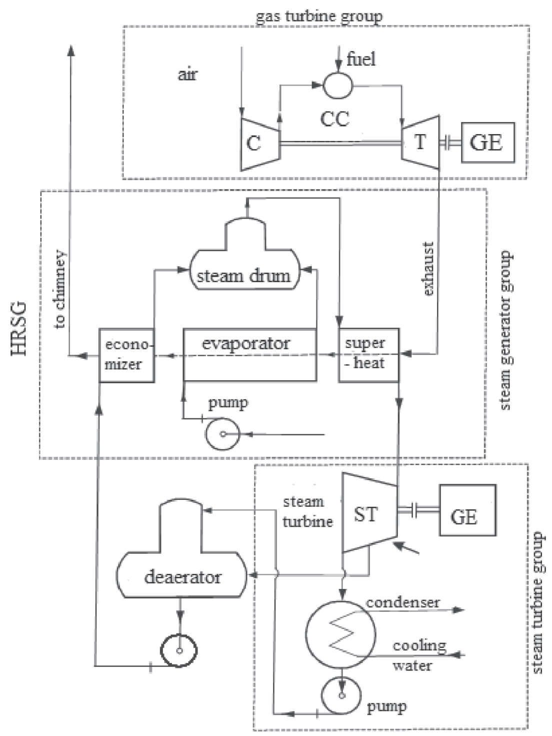

Figure 1. Main elements of the simplest Combined Cycle Gas Turbine (CCGT), where: GT – gas turbine, C – compressor, CC – combustion chamber, GE – electric generator, HRSG – heat recovery steam generator, ST – steam turbine.

There is power unit 'superstructured' by gas turbine system working in significantly higher temperatures range (Fig. 2) than steam turbine. In this purpose can be used for example mercury vapor, air or (common used) combustion gases generated in the combustion chamber of the gas turbine as working medium. By rising tempereture of top heat source – he reached much higher efficienty for all set of power housues. Another way is lowering temperature of down a heat source. It takes the opportunity to use a low temperature waste heat source. In this case working medium must be – instead of water – fluid with significantly lower boiling point. There is named organic Rankine cycle (ORC). By 'understructure' steam

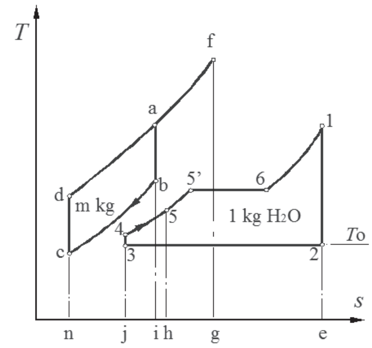

Figure 2. Temperature-entropy diagram of combined-cycle gas turbine/steam turbine.

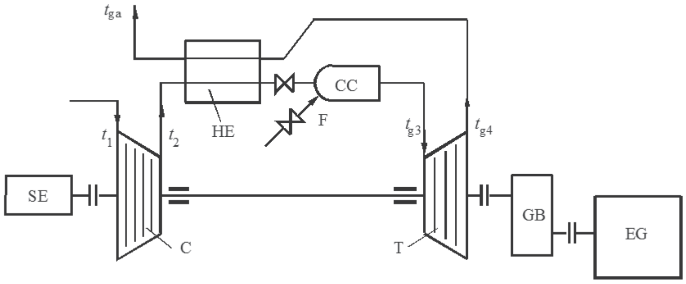

Figure 3. Internal combustion open system (direct heating): SE – starting engine, C – compressor, T – gas turbine, GB – gearbox, EG – electric generator, CC – combustion chamber, F – fuel inflow, HE – heat exchanger (regenerator), t_1 – inlet air temperature to compressor, t_2 – compressed air temperature, t_{g3} – temperature of the exhaust gas flowing into the turbine, t_{ga} – exhaust gases temperature.

power unit of gas turbine system – for example freon or pentane vapor – it is able to increase efficiency of power station.

Diagram of a system with heat regeneration and internal combustion is presented in Fig. 3. Here, the hot exhaust gases from the turbine are passed through a heat exchanger (regenerator – HE), to increase the temperature of the air leaving the compressor (C) prior to combustion. This reduces the amount of fuel needed to reach the desired turbine-inlet temperature.

3 Turbogas system with the external combustion

The example of the open system about external combustion (in exhaust side) is presented in Fig. 4 – turbine blades have not got any contact with combustion gases which is important adventage. The working blade is most loaded turbine element because of the impact of high temperatures and the dynamic forces (pulsating tangential and centrifugal forces). Buckets vibration are the most common phenomenon leading to the turbine failure. In open system in Fig. 4 problem of blades contact with the exhaust gases has been statically operated working heat exchangers:

- exchanger HE I – low temperature exchanger (also tittled 'cold' exchanger or first-degree exchanger),
- exchanger HE II – 'hot' exchanger in which air working temperature reaches nominal value t_3.

Outlet air (out from the turbine) temperature t_4 divided into two streams:

- combustion air supply combustion chamber CC,
- pass through the bolt Z1 to the heat exchanger HE I.

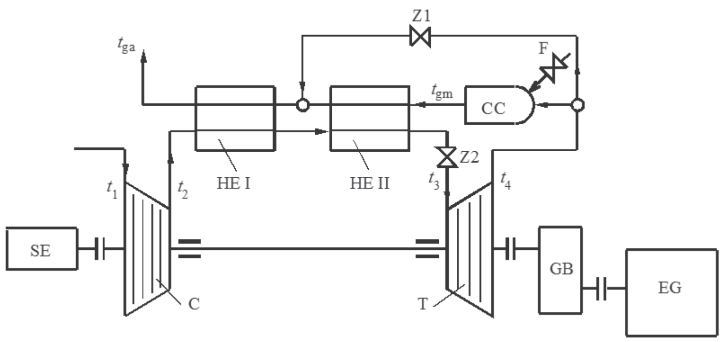

Figure 4. External combustion open system (exhaust heated): SE – starting engine, C – compressor, T – gas turbine, GB – gear box, EG – electric generator, CC – combustion chamber, F – fuel inflow, HE – heat exchanger (regenerator), t_1 – inlet air temperature to compressor, t_2 – compressed air temperature, t_{g3} – temperature of the exhaust gas flowing into the turbine, t_{ga} – exhaust gases temperature.

In Fig. 5 there is presented closed system about the same like in Fig. 4 elements. The only difference is that outlet air from turbine temperature t_4 is directed back to compressor C as air temperature t_1 by using after cooler (CH) which cooler medium is water in constant temperature. The combustion air is fed through the blower (BL) (powered by engine AG). As heat medium could be taken gas or high temperature steam from another source.

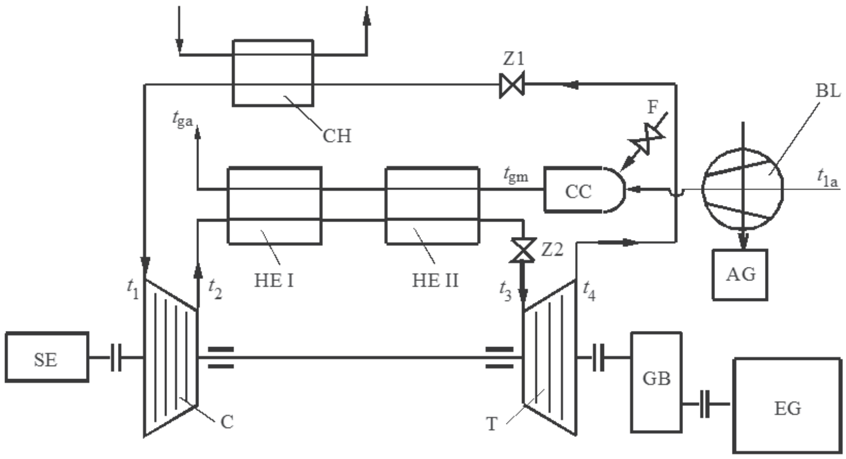

Figure 5. External combustion closed system (indirect heating-closed cycle): AG – blower engine, SE – starting engine, C – compressor, T – gas turbine, GB – gearbox, EG – electric generator, CC – combustion chamber, F – fuel inflow, HE – heat exchanger (regenerator), t_1 – inlet air temperature to compressor, t_2 – compressed air temperature, t_{g3} – temperature of the exhaust gas flowing into the turbine, t_{ga} – exhaust gases temperature.

4 Modified system

Classic open system, with heating in exhaust side, has rather low thermal efficiency (15–20%) therefore there has been presented concept of expanded system equipped with additional heat exchangers and the corresponding combustion chamber. In order to improve the performance of the system like in Fig. 4 the air pressure of working fluid should be rised . Then compression with inter-cooling and multistage expansion in turbine with heating air (equivalent of interstage superheating steam in the Rankine system) are neccesary. In Figs. 6 and 7 there is presented exampled system composed of four turbines (T1–T4), four compressors (C1–C4) and three heat exchangers (regenerators) integrated with combustion chambers and three consecutive intercoolings (CO1–CO3) and also special preliminary blower (B) (combustion is atmospheric). There has been adopted the principle of 'free shaft'. It is four-stages set of four turbine – two high-pressured turbine driving all four air compressors and two another ones (low-pressured) driving electric generator.

Figure 6 is a results numerical example. Lines 1-a-b-c-d-e-f-2 mean particular compression and interstage cooling. Compression ratio are identical in all compressors and all temperatures are equal. Curve 2-2a and 2a-2b segments mean two-stage process of compessed air heating in 'cold' (countercurent) heat exchanger by exhaust gases leaving 'hot' heat exchanger. Segment 2b–2c presents the amount of heat transferred to compressed air in 'hot' heat exchanger (first stage, HHE1), while segment 2c–3 means suitable amount of heat transferred to this air in second stage exchanger (HHE2) before reaching temperature t_3. Segments (3-a-b-c-d-e-f-4) mean respectively expantion processes and working air heating up. Segment 4–4a means decrease temperature of air leaving the last turbine, caused by mixing this air with an additional amount of cold air supplied by blower. Point 4a means parameters of air condition supplied to the combustion chamber ('atmospheric' combustion).

For this way modified system, with using five-casing compression, it could be reached thermal efficiency with value over 40%.

5 Bleeding of compressed air

An air/steam installation can be very useful while cooperation with process plant giving an possibility to supply by compressed air jet with expected temperature and appropriate pressure. Then turbine system becomes an installation producing electric energy and simultaneous supplied industry plant by compressed air on a discount. General thermal efficiency of this system reaches then much higher values. If turbo-gas system (rather turbo-air) with exhaust side heating produces only electric energy and his thermal efficiency is about 33%, general efficiency while working with air discount will reach general efficiency (degree of utilization of the energy contained in fuel) while working with air discount is over the level of 70%. Exampled installation is presented in Fig. 8.

6 Coupled systems of air and steam turbines

Next, an air turbine system with external combustion could be extended with steam turbine system using heat of combustion gases of air turbines installation. In the air turbine system there is used 4-times compression with intercooling and four-level expansion with 3-times superheating, while the steam turbine system is using double overheating and condensation. Then, despite of relatively large pressure loss on the side of the combustion gases, it is achieved overall efficiency of 50% the power station (in clutches of turbines). As fuel is assumed natural gas. Example of this installation is shown in Fig. 9 and related with it temperature-entropy diagram in Fig. 10. Another proposition is presented in Fig. 11.

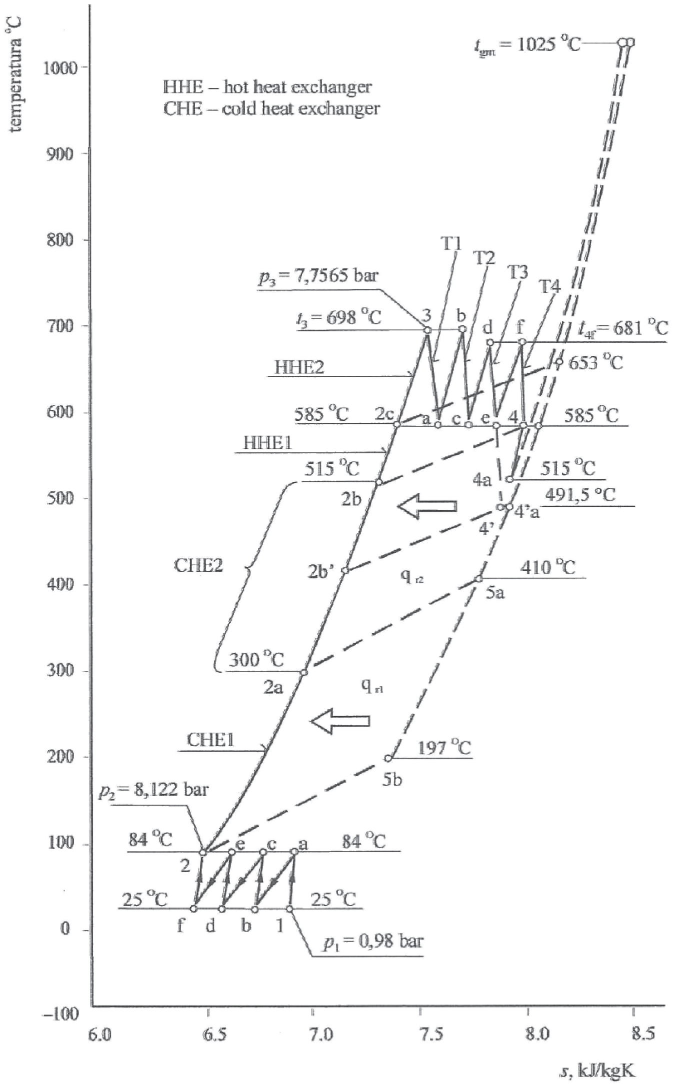

Figure 6. Temperature-specific entropy diagram for working air and exhaust for modified system with combustion in exhaust side: q_{R1} – heat supplied in exchanger CHE1, q_{R2} – in exchanger CHE2.

7 Another examples

Results of performed analysis suggest that most preffered systems are configurations producing power in proportion: 4C/4T, 4C/3T or 3C/3T because of their quite high overall efficiency and sets: 1C/4T or 1C/3T because it is easy to use it

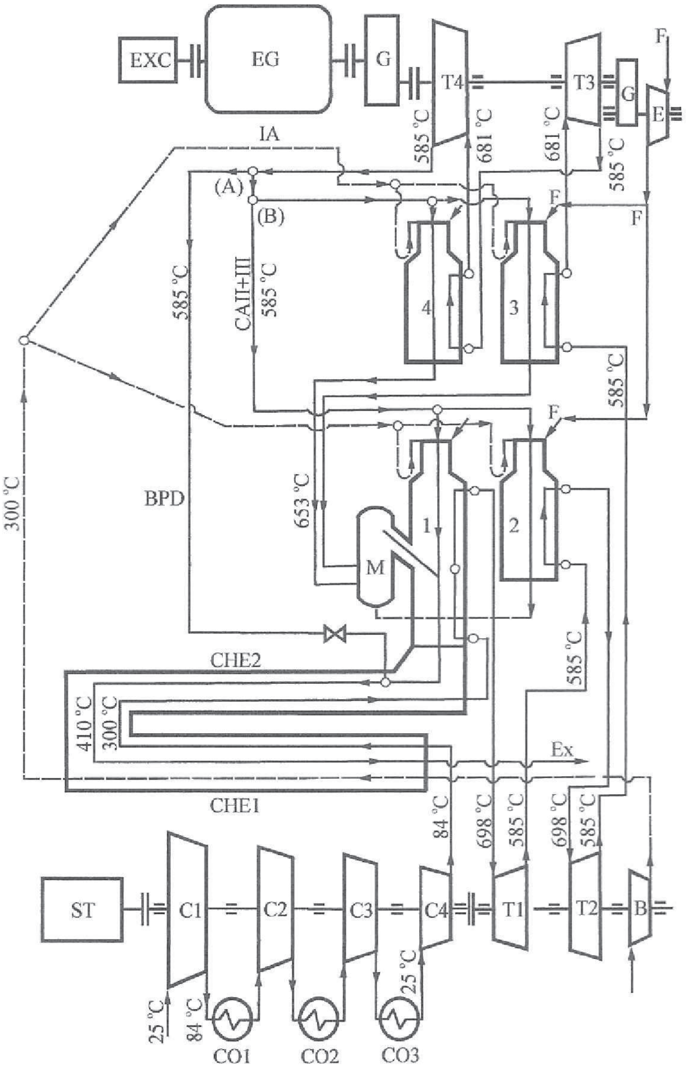

Figure 7. Scheme of modified turboair system with external combustion: B – blower, BPD – bypass channel, C1-C4 – compressors, CAII+III – secondary and third air hoses, CO1-CO3 – inter-coolings, CHE1 and CHE2 – 'cold exchangers', E – gas expander, EG – generator, EXC – exciter, F – fuel (natural gas), G – gear, IA – first air hoses, M – exhaust mixer, ST – starting engine, T1-T4 – air turbines, 1-4 – combustion chamber integrated with the relevant heaters, Ex – exhaust to atmosphere.

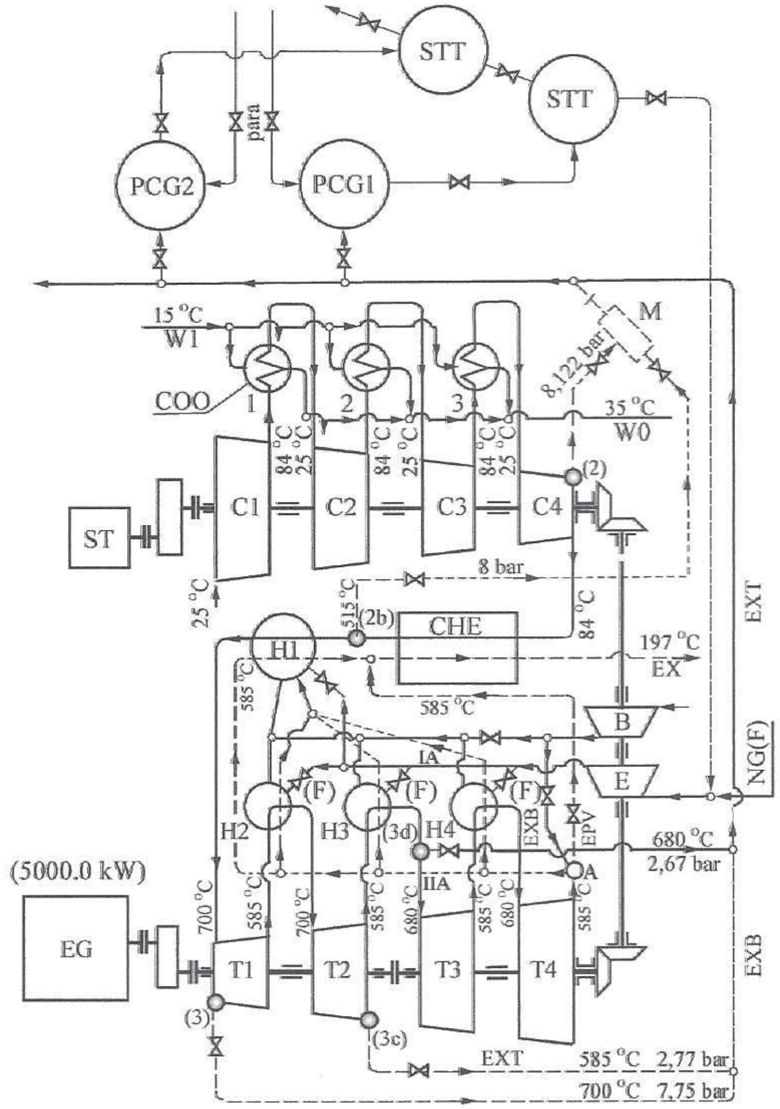

Figure 8. Scheme of four-stages installation external combustion supplied in addition high-pressured generator of coal gas. Designations: EG – electric generator; T1, T2, T3, T4 – air turbine units; C1, C2, C3, C4 – compressor's units; ST – starting engine; E – gas expander; B – blower; CHE – 'cold' heat exchangers; H1, H2, H3, H4 – 'hot' heat exchangers integrated with combustion chamber; F – fuel (natural gas); BPV – by pass duct valve; EX – outlet; EXT – outlet cord; (2), (2B), (3), (3C), (3d) – discount points; A – mixing tank outlet air from turbine T4 and the air supplied by blower; COO – intercoolers tagged numbers 1, 2, 3; W1 – water inflow; W0 – water outflow; M – mixig ejector; PCG – high-pressured coal gas generator; STT – storage tanks produced gas; NG(F) – natural gas retrieved from another source.

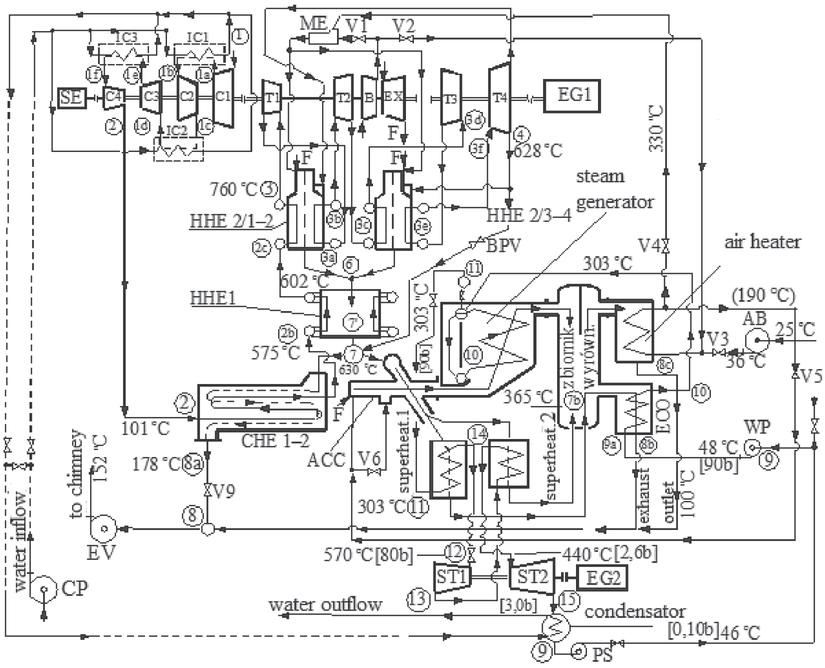

Figure 9. Scheme of combined plant with division of mass stream: T1-T2 – turbines driving compressors team; T3-T4 – useful power turbines; B – blower; BPV – circular valve; F – fuel; CC – main combustion chamber; ME – mixig ejector; V1-V9 – valves and gate valves; ACC – auxiliary combustion chamber; AB – auxiliary blower; SG – steam generator; S No.1 – steam superheater; S No.2 – interstage steam superheater; CAP – air combustion heater; WP – condensate pump; CHE No. 1-2 – low-temperature exchangers; HHE No.1-2 - high-temperature exchangers; ST1/2 – high-pressure/low-pressure steam turbine; EG No.1-2 – electric generators; EX – natural gas expander; C1-C4 – air compressors; SE – starter engine; IC No.1-3 – intercoolers; CP – cooling water pump.

as combined air/steam cycle with cogeneration. Symbols C and T denote, respectively, compressors and turbine components, while numbers refer the number of compression and expansion processes. In fact, only one of these sets can be considered as optimal, depending on the discretion which aspect is more important: the highest thermal efficiency (fuel consumption) or minimum costs of installation building (minimum number of turbine and compressor units). Exampled systems are shown on Figs. 12 and 13.

Given examples lead to conclusion that combined air/steam power plant with cogenerator create many variants of energy utilization but this domain requires additional studies in this area. Authors of these systems limited their analysis to only those which produce power.

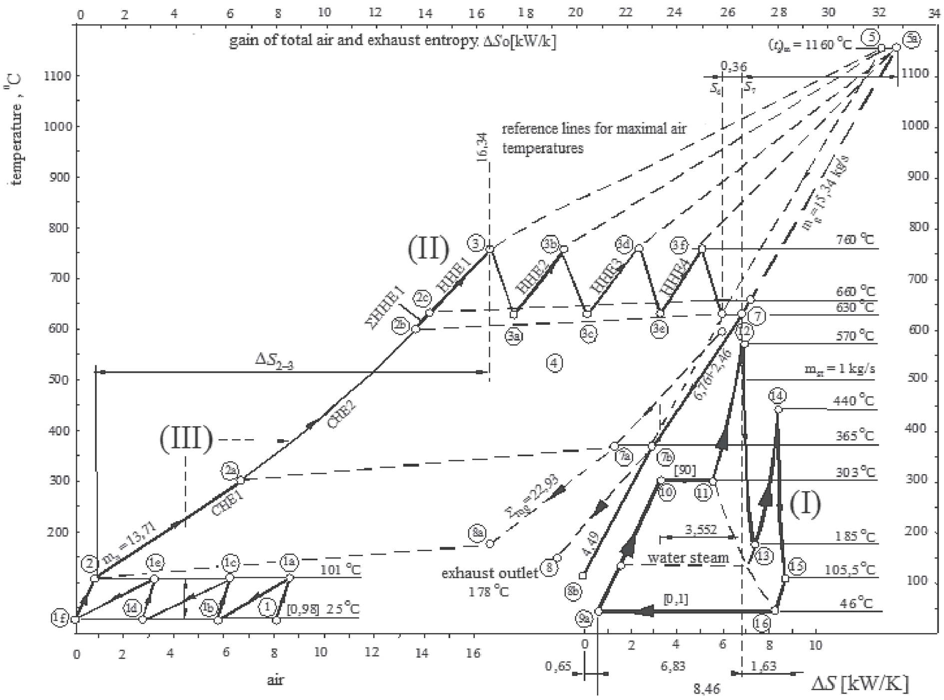

Figure 10. Temperature-entropy diagram of combined air/steam cycle.

It can be assumed that multi-stage combined systems with heating the exhaust side will find in the near future more common industrial use, because they allow to obtain high thermal efficiency at a moderate inlet temperature and because of their undeniable advantages of using external combustion, especially when it comes to the carbonaceous fuel and other heavy fuel oil.

8 Pulverized coal-fired power plant

There have also been analysed cases of combined (binary) power plant – air/steam stations with particular emphasis on combustion chamber to pulverized coal, equipped with radiation screens for heating the working air turbines. While considering there had took into account one and two radiation screens systems using two working fluid.

There were also taken into account multistage open systems using two working fluids with external combustion – multicompressor and multiexpander working air systems, with multistage cooling. It was the only way to reach high unit power in kW/kg working air per second or minimal air consumption of processed on exhaust gases.

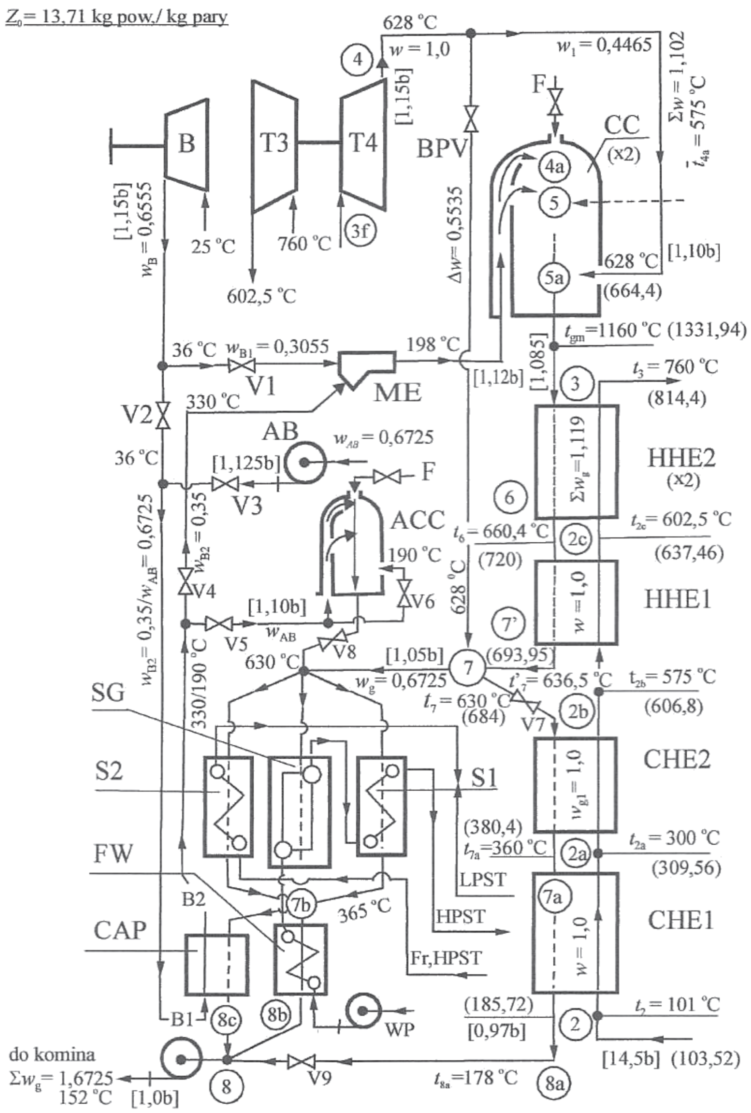

Figure 11. Scheme of installation including the connected mass stream of working fluids: AB – auxiliary blower; ACC – auxiliary combustion chamber; B – blower; BPV – circular valve; CAP – combustion air preheater; CC – main combustion chamber; CHE No.1-2 – low-temperature exchangers; F – fuel; FW – economizer; HHE No. 1-2 – high-temperature exchangers; LPST/HPST – low-pressured side of turbine/high-pressured side of turbine; ME – mixing ejector; S1 – steam heater; S2 – interstages steam heater; SG – steam generator; T3-T4 – useful power turbines; V1-V9 – valves and gate valves; WP – feed pump.

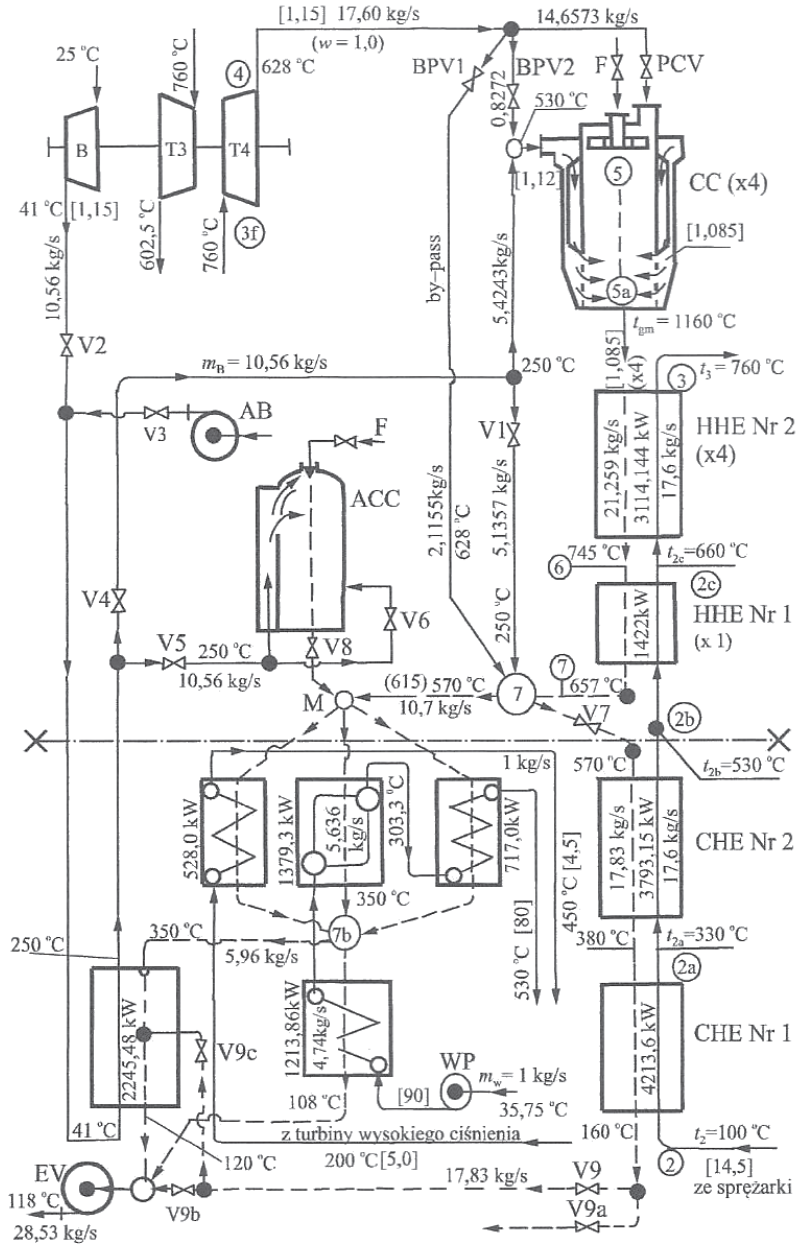

Figure 12. Flow diagram of binary power plant: AB – auxiliary blower; ACC – auxiliary combustion chamber; B – blower; BPV – circular valve; CC – combustion chambers (four combustion chambers cooperated parallel but only one shown in diagram); EV – exhaust ventilator; F – fuel inflow; HHE and CHE – 'hot' and 'cold' heat exchangers; PCV – primary and secondary air control valves; T1-T2 – turbines driving compressors set; T3-T4 – useful power turbines; M – air mixer.

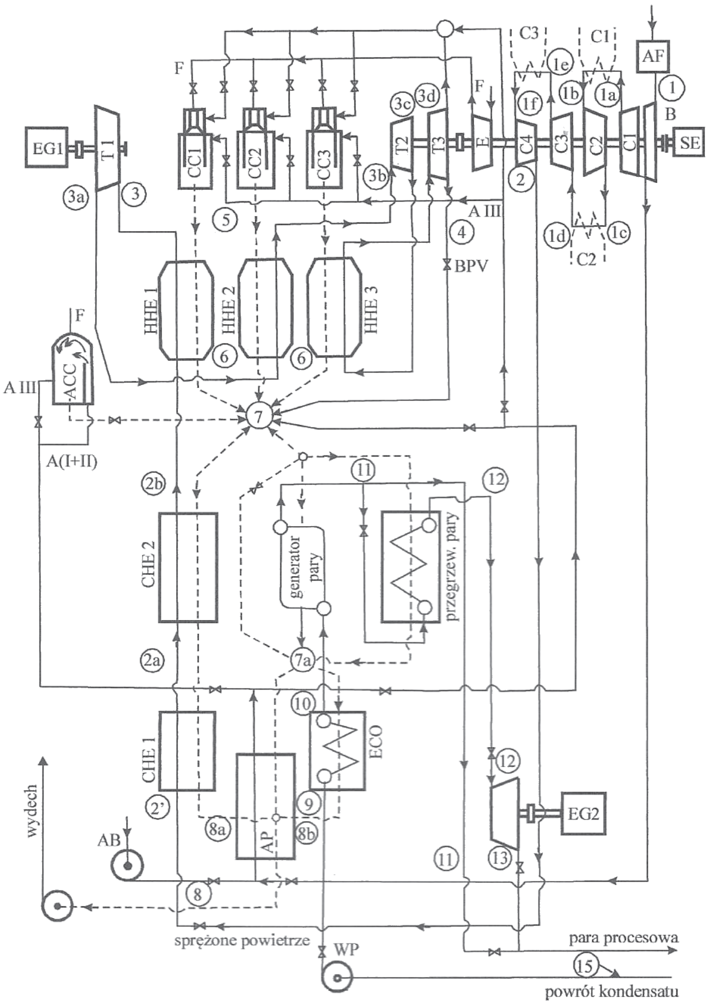

Figure 13. Schematic diagram of combined air/steam cycle with the expansion of the air, and a single expansion steam; the steam of outlet is used as process steam, where: AF – air filter; B – blower; AB – additional blower; IC1-IC3 – intercoolers; EG1 and EG2 – electric generators; C1 to C4 – set of compressors; T1 to T3 – jet of air turbine, F – fuel gas; E – expander; A-I, A-II, A-III – combustion air; SE – starter engine; CC – combustion chamber; ECO – economizer; WP – circulating pump.

In considered open systems there are two working fluids: compressed air and steam. The air heats up in special high-temperature heat exchangers and combustion chambers (one or several ones) function only as a source of exhaust heat or also this air is heated in the pipe system covering the walls of the combustion chamber (being called: radiation screens of flame and combustion gases).

Steam to drive steam turbines or for the purpose of the process is produced in a separate generator, which is in the so-called heat recovery steam generator (HRSG). This generator uses heat contained in the exhaust gas heat exchanger outlet or produces it in air tube radiation screens which covering radiation wall of the combustion chamber.

The latest production of the high-pressure superheated steam is well known in the practice of the boiler. Examples of such power are provided in Figs. 14 to 17. In Fig. 14 there is shown scheme of combined air/steam cycle with a three-stage air turbine, without radiation screens and with cogeneration. Figure 15 presents scheme of combined air/steam cycle with a three-stage air turbine and with radiation screens. In Fig. 16 there is shown schematic diagram of combined air/steam cycle with a three-stage air turbine, with air tube radiation screens and with cogeneration. Figure 17 presents scheme of combined air/steam cycle with a three-stage air turbines, with two waterwalls systems in combustion chambers for two stages of air turbines T1 and T2. In Fig. 18 there is shown an example of the design concept of the combustion chamber (with two air tube radiation screens systems) and high temperature heat exchanger for multistage combined air/steam power plant.

9 Summary

In presented Professor Goliński and Jesionek works in the purpose of established and implemented by them program about air turbine system there was intentionally omitted all issues widely discussed in the literature about air/steam systems with gas turbines with (internal) direct combustion. It was solely focused on these binary power station, in which the working medium are the air and steam. There were considered complex systems of compressors, air and steam turbines (with external combustion), exchangers and combustion chambers, in which combustion gases are used to heating up working air and generate steam. All discussed systems are usefull in order to co-generate and to industrial energy.

In Professors works there were presented principle of construction these multistage systems and documented the benefits of combination air turbines unit with steam turbine. The most important benefit is total thermal efficiency of two-fluids (binary) systems is level from 44% to 50% and even more. External combustion system is particularly well suited for combustion of heavy fuel oil, like those which are used in conventional steam power plants.

Presented in works of Professors numerical examples are not quite accidental. Though they constitute a collection of painstakingly collected figures, algorithms, computational and painstakingly made, detailed calculations (especially the bal-

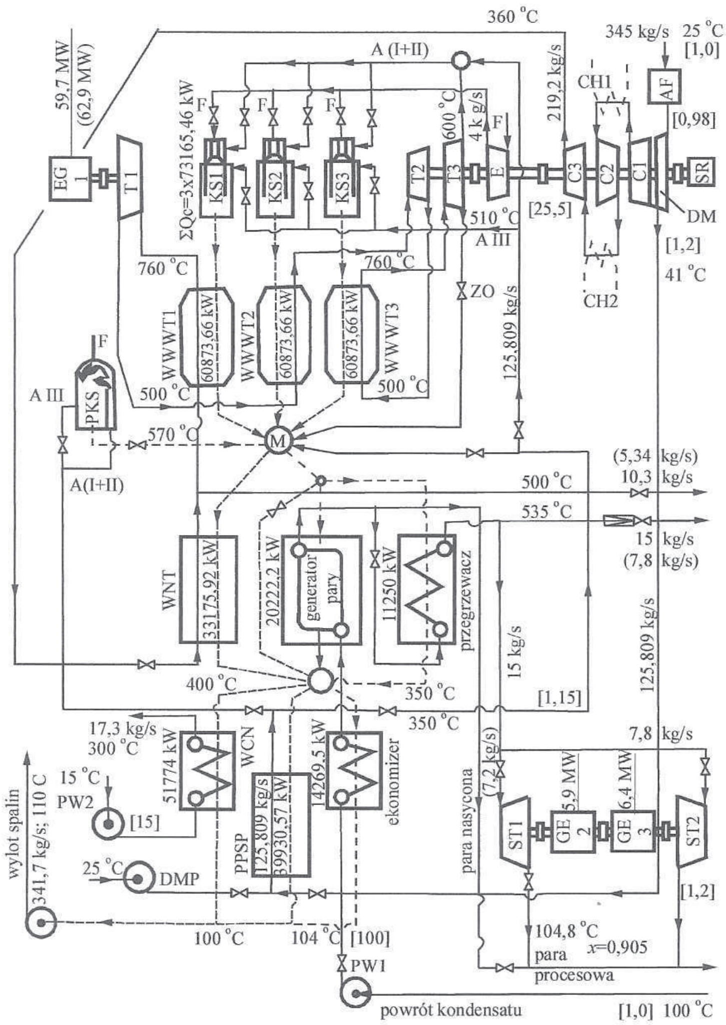

Figure 14. Schematic diagram of combined air/steam cycle with a three-stage air turbine, without radiation screens and with cogeneration: T1 to T3 – set of air turbines, high-, medium- and low-pressure turbine, respectively; C1 to C3 – set of working air compressor; CC1 to CC3 – set of combustion chamber; WWT1-WWT3 – set of high temperature-heat exchangers; M – mixer; PKS – auxiliary post combustion chamber; WNT – low-temperature heat exchanger; M – mixer; WCN – excess air heat exchanger; PSP – combustion air heater; ST1 and ST2 – steam turbines, DMP – secondary blower; PW1 and PW2 – water pumps; WW –exhaust fan; GE1-GE3 – electric generators; CH1 and CH2 – intercoolers; AF – air filter; DM – blower; SR – starting engine; F – supply of natural gas.

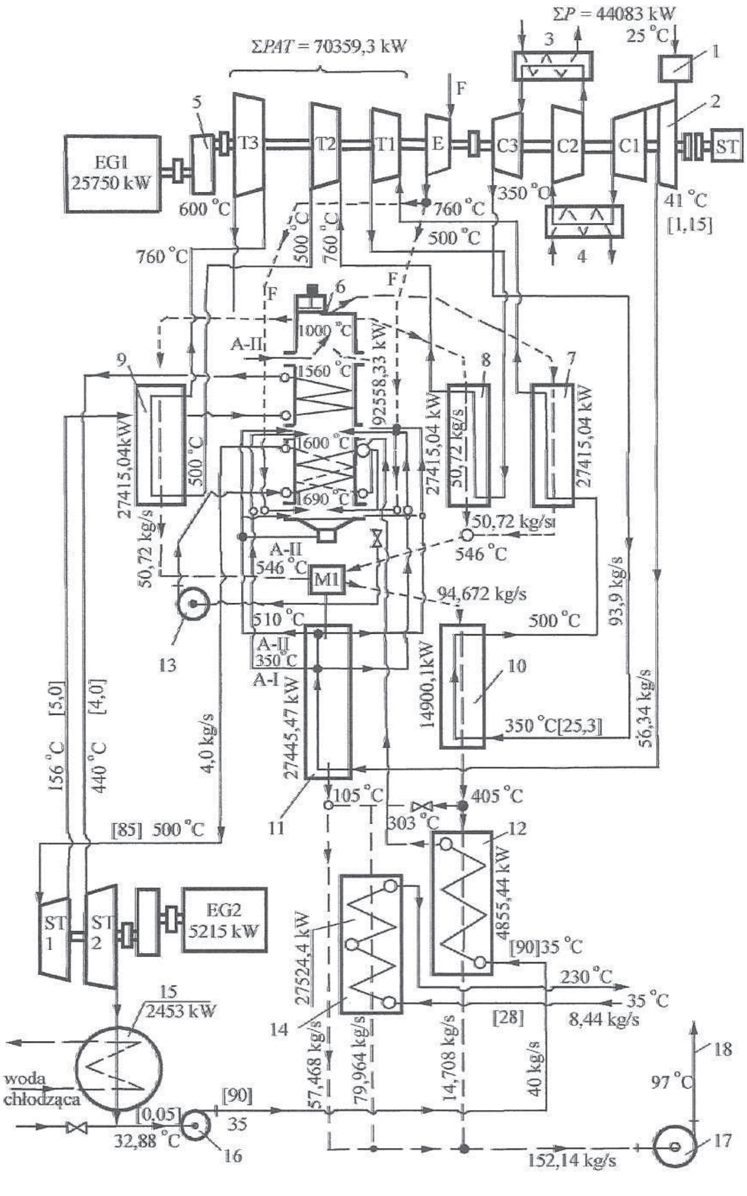

Figure 15. Schematic diagram of combined air/steam cycle with a three-stage air turbine and with radiation screens: 1 – air filter; 2 – blower an additional combustion air; 3 and 4 – intercoolers; 5 – gear; EG1 and EG2 – electric generators; C1 to C3 – set of compressors; T1 to T3 – set of air turbine, F – fuel gas; E – expander ; A-I, A-II, A-III – combustion air; SE – starter engine , ST1 and ST2 –steam turbines; 6 – combustion chamber; 12 – economizer; 13 – circulating pump; 14 – excess air heat exchanger; 15 – condenser; 16 – condensate pump; 17 – exhaust fan, 18 – outlet of exhaust gases into the atmosphere.

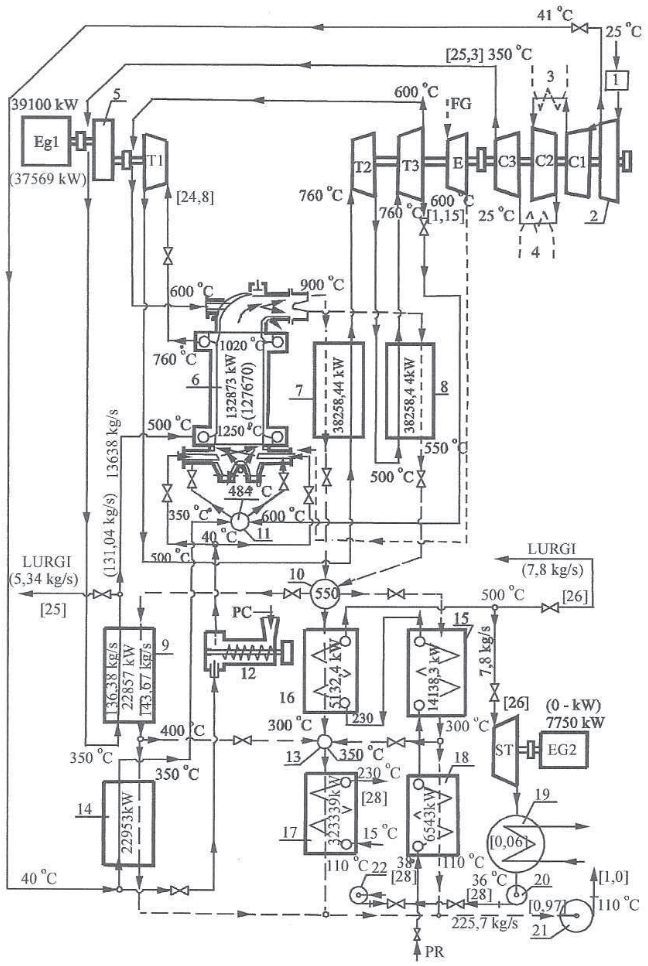

Figure 16. Schematic diagram of combined air/steam cycle with the high-pressure (three-stage) air turbine, with air tube radiation screens: EG1 and EG2 – electric generators; T1 to T3 – set of air turbine; FG – fuel gas (to start); E – expander; C1 to C3 – compressors, LURGI – high pressure coal gas generator; PC – pulverized coal: ST – steam turbine; PR – return condensates from the processing installation process; 1 – air filter application to blower; 2 – blower, intended as part of an initial low pressure compressor; 3 and 4 – interstage compressed air coolers; 5 – gear; 6 – combustion chamber with an air-tube screens and burners (placed in the corners); 7 and 8 – high-temperature heat exchangers; 9 – low-temperature heat exchanger; 10 – combustion gas mixing tank; 11 – mixer of combustion air; 12 – device giving the pulverized coal; 13 – low-temperature exhaust mixer; 14 – combustion air proheater; 15 – steam generator; 16 – superheater of steam; 17 – excess heat receiver; 18 - economizer; 19 – condenser; 20 – condensate pump; 21 – exhaust fan; 22 – auxiliary pump (where using bleed of steam).

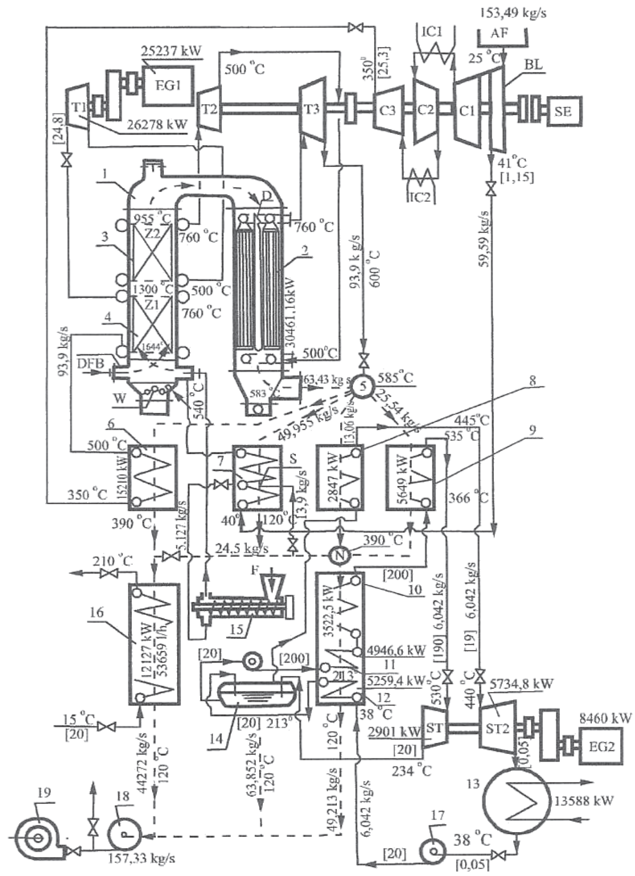

Figure 17. Schematic diagram of combined air/steam cycle with three-stage air turbine with radiation screens for two stages of air turbines T1 and T2: AF – air filter; BL – blower; SE – starting engine; C1 to C3 – three-stage compressors; T1 to T3 – three-stage air turbines; EG1 and EG2 - electric generators; ST1 and ST2 – steam turbines (high- and low-pressure); N – mixer of exhaust gases; F – chute of fuel; DFB – an alternative fuel supply burners (coal dust or natural gas); D – gate valve for the regulation of extraction of exhaust flow; W - water-cooled grate; 1 – the upper part of the combustion chamber provided with a safety valve; 2 – high-temperature heat exchanger; 3 – radiation screens for medium-pressure (T2) turbine supply ; 4 – radiation screens for high-pressure (T1) turbine supply; 5 – mixer of air and exhaust; 6 – low-temperature heat exchanger (regenerator); 7 – two-staged combustion air preheater; 8 – low-pressure steam superheater; 9 – high-pressure steam superheater (200 bar); 10 – high-pressure steam generator; 11 – high-pressure economizer; 12 – low-pressure economizer; 13 – condenser; 14 – surge tank (vaporiser); 15 – feedeing device coal dust; 16 – excess heat receiver; 17 – low pressure pump of condensate; 18 – exhaust fan; 19 – cyclone dust separator.

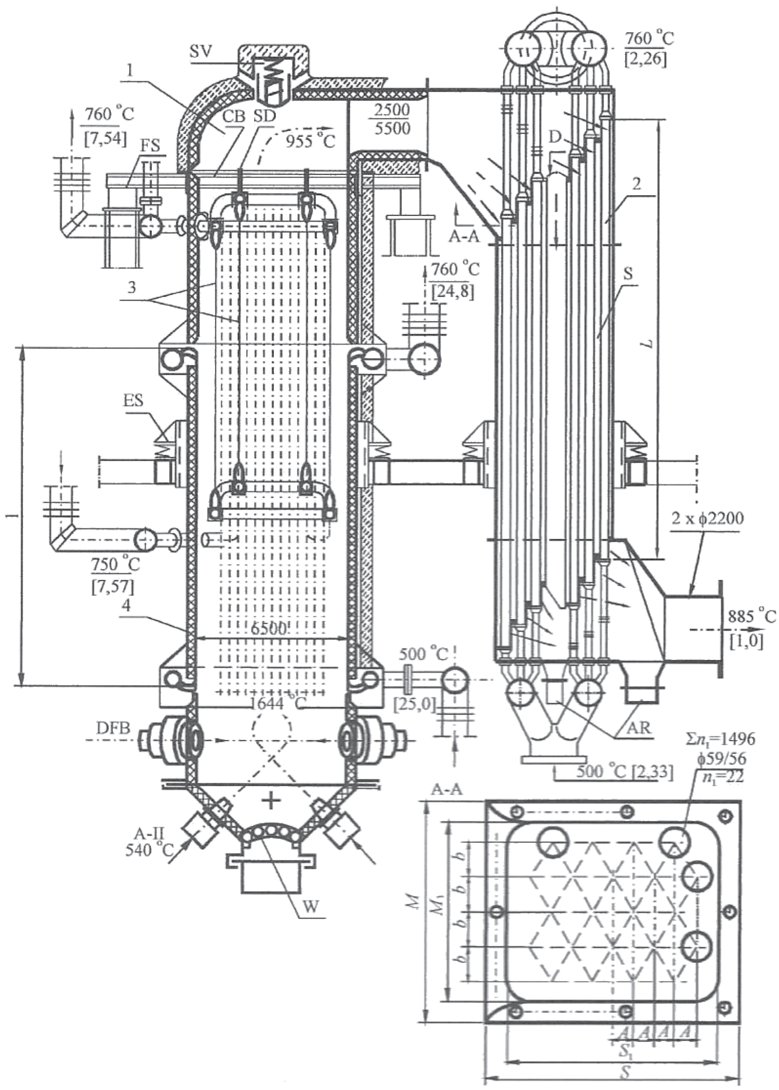

Figure 18. Concept of the combustion chamber: SV – safety valve (outlet an explosive), FS – is a permanent suspension of the combustion chamber and the top of the waterwall, CB – beams (water-cooled), SD – ties carring, D – gate valve for regulating of combustion gases flow, ES – spring support, DFB – burners pulverized coal and natural gas to start the installation (4-placed in the corners), A-II – additional secondary air, W – water-cooled grate; AR – ash box, 1 – cover of combustion chamber, 2 – high temperature heat exchanger; 3 – hanging upperset of radiation screens on top, 4 – lower set of radiation screens supported on the walls of the chamber; S, S1, M, M1 – dimensions.

ance sheet) for the proposed power plants. Therefore it can be concluded that the works [1] and [2] represent a significant technical potential. Concern because a number of complex, interpenetrating issues thermomechanical several areas of mutually. Because there is no practice problem-solving techniques of completely isolated thermal zones. Considering issues from thermodynamics, including phenomena meant statically and chemistry of combustion, through fluid mechanics and heat exchange, to calculations and construction of combustion chamber and radiation screens, it clear that both knowledge resource required by the constructor elements in thermal power plants as well as his experience must be very large, especially when it comes to the whole of the proposed project.

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