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JACEK TOPOLSKI, JANUSZ BADUR*

Comparison of the combined cycle efficiencies with different heat recovery steam generators

Institute of Fluid-Flow Machinery PAS, Fiszera 14, 80-952 Gdańsk, Poland

Abstract

While most attention of combined cycle developers focus on the gas turbine, only a few papers turn into the steam cycle beginning with the heat-recovery steam generator (HRSG). Therefore, in this paper it has been undertaken the problem of optimal utilisation of the flue gas recovery heat within differently organised HRSGs. For selected advanced ABB GT26 gas turbine composed with four different HRSGs the combined cycle have been analysed parametrically using own computer code COM-GAS. The maximum efficiency with respect to steam turbine parameters like power, live steam pressure, has been calculated for four HRSGs with different arrangements of heat exchange surfaces.

Keywords: Gas turbines; Flue gas; Heat recovery steam generators; Combined cycles

Nomenclature

1P	–	single pressure HRSG, Fig. 3	LP	–	low pressure
2P	–	dual pressure HRSG, Fig. 4	$\dot{m}$	–	mass flow rate, kg/s
3PA	–	triple pressure HRSG, Fig. 5	ST	–	steam turbine
3PB	–	triple pressure HRSG, Fig. 6	HRSG	–	Heat Recovery Steam Generator
CC	–	combined cycle	evap	–	evaporator
GT	–	gas turbine	eco	–	economizer
HP	–	high pressure	sh	–	superheater
IP	–	middle pressure	cph	–	condensate preheater

1 Introduction

According to J.-L. Poiriel's presentation at POWER-GEN'2000 [24], the private power producers now control about 25% of the energy market. It is not

*Corresponding author. E-mail address: jb@imp.gda.pl

too much but within the next decade the private power producers will control 55% of the total market and 95% of modern and efficient power production. It means, tomorrow's power producers, will have to achieve a "critical mass" of generating assets to complete in the interstate market-place.

The marchant developing of the private power producers market is important from two reasons. The first one is that in Poland private power producers would be only a one real force which, from engineering point of view, will have chance to achieve a "critical mass" of technical and business efficiencies for pushing forward our domestic un-flexible, uneconomic, obsolete, anti-ecological power market [23]. The second reason, important for this work, is that the combined cycle technology – being fundamental tool for private power producers, is offering the highest thermal and economical efficiency of all heat and electric generating systems, commercially available today [4]. It also exhibits capital costs that are lower then competing nuclear and coal fired steam plants and dramatically lower than power plants based on renewable energy projects. There is no surprise that almost all marchant project developers in Poland have specified the combined cycle technology.

Together with more advanced conversion systems with e.g. gasification of solid fuels and biomass, organic Rankine cycles, heat pumps, fuel cells, in order to achieve the desired technology, very complex plant configurations are often nowadays required. To be possible to calculate a plant with about 200 apparatus, the advanced software tools are required. Therefore, nowadays the renaissance of classical computing methods is observed. It can also be observed that *Computational Fluid Thermodynamics* (CFT) generally develop within two bifurcated branches: CFD (*Computational Fluid Dynamics*) for local, 3D description of unknown fields and CFM (*Computational Flow Mechanics*) for integrated, so-called 0D description of unknowns parameters of the power plant apparatus.

This paper aims at presenting thermodynamical analysis of different gas-fired combined cycle power plants based on the ABB GT26 engine. Our analysis will be performed using an in-house code COM-GAS for multi-variant design of an advanced combined cycle in different configurations of the plant's apparatus. The common assumption is a 2-1-1 configuration (two GT26 engines, one HRSG, one Steam Turbine of 200 MW type) and different options will be obtained with four differently arrangement Heat Recovery Steam Generators.

2 Combined cycle scheme

All the combined cycles compared and analysed in the paper have been optimized with respect to the maximum plant efficiency. Such an analysis and optimization process is subjected to various constraints, many of which are mainly technological.

Let us assume the power plant concept for a longitudinal arrangement of the main plant structure. In Fig. 1 is shown the scheme of combined cycle which contains two ABB GT26 engines with output of 240 MW, that produces relatively hot flue gas at temperature $\sim 610^0$C and exhaust mass flow $\sim$ 540 kg/s. Since, according to manufacturer data [6,7,11], any HRSG without supplemental firing needs for heating of 1 kg/s of steam up to 550^0C about $5.5 \div 8$ kg/s of flue gases, therefore, for proper heating of $\dot{m}_{steam}$ = 147 kg/s in the 200 MW type steam turbine is needed from $\dot{m}_{flue\ gas}$ = 800 kg/s to $\dot{m}_{flue\ gas}$ = 1300 kg/s of hot flue gas. The exhaust gas from the gas turbine flows axially via the collector to the Heat Recovery Steam Generator (HRSG) before being discharged to the atmosphere via a stack at a height of 60 m. The HRSG (similar to RAFAKO's type [22]) is of the natural circulation drum type in a horizontal arrangement. The additional apparatus like: gas supply, air supply, ventilation system, fuel preheater, boiler feedwater pump, will be at this stage of analysis, neglected. Also, the steam cycle with high-, intermediate- and low-pressure parts will be modelled "roughly" but with the identical thermal conditions four all compared versions of the HRGS.

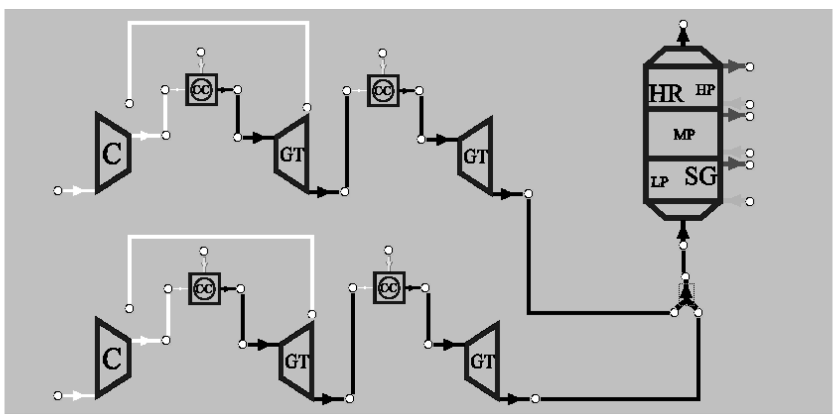

Figure 1. Scheme of combined cycle with the GT26 engine in 2-1-1 configuration.

3 The gas turbine GT26

The ABB GT26 engine has been selected for this study because it has particular characteristics such as the exhaust temperature being about 30^0 C higher then in competing machines (for instance: Westinghouse's 501 F-550^0C, $\dot{m}$ = 449 kg/s, Siemens' V84.3 – 560^0C, $\dot{m}$ = 624 kg/s, General Electric's MS9001FA – 580^0C, $\dot{m}$ = 615 kg/s). The GT26 at 240 MW is the largest 3000 rev/min gas turbine now available for the 50 Hz market. It has 37.8% simple cycle efficiency and 58.5% in a combined cycle. With a sequential combustion it ensures that both a high exhaust gas temperature and a high power conversion per kilogram of air drawn in are achieved [21]. The sequential combustion realised in low-emission EV and EVS- burners, respectively, is characterising by flame-less oxidation in the second stage of an annular combustion chamber. In Fig. 2 it is shown, for a comparison, on the $i - s$ diagram, the standard gas turbine process with the sequential combustion process. The data for GT26 are presented in Tab. 1.

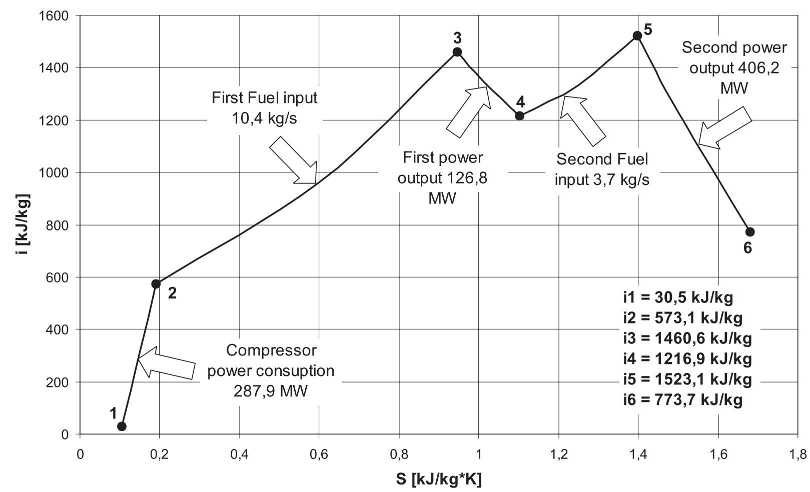

Figure 2. The principle of sequential combustion in GT26 according to [19,20].

4 Advanced Heat Recovery Steam Generator (HRSG)

Besides continuous development in design and performance of gas turbines for power generation, tremendous progress is being made in HRSG technology [22,8-10]. Increasing sizes, exhaust gas turbines ($t > 600^0$C) and mass flow ($\dot{m}_{flue\ gas} > 540$ kg/s) of the recent gas turbines are having a major impact on new advanced HRSG design [22]. Nowadays' designs need to incorporate many more features to ensure optimum efficiency [18]. Therefore, in the paper we want to consider four different HRSG which are particularly patterned on the RAFAKO's production [22], NEM Energy [8], EVT Energie-und Verfahrenstechnik [12].

The first HRSG is a single pressure non-reheat cycle (Fig. 3) taken here rather as a base for comparisons. The second one is a dual pressure non-reheat cycle (Fig. 4). It consists of two (IP+HP) evaporator systems designed for parallel

Table 1. GT26 data characteristics (in ISO conditions, natural gas) [6,7]

Gross output [MW]	241
Gross efficiency [%]	37,8
Compressor pressure ratio [–]	30
Exhaust mass flow [kg/s]	542
Exhaust temperature [^{0}C]	610
Inlet temperature [^{0}C]	15
Ambient pressure [bar]	1.013
Shaft speed [rev/min]	3000
Fuel – natural gas [MJ/kg]	42
NOx emission [ppm]	< 25 (natural gas)
Number of stages:	
Compressor	22
Turbine	$1+4$
Dimensions [m]:	
Lenght	12.3
Width	5
Height	5.5
Weight [ton]	335

flow operation, two drums, IP economiser, two HP economisers and IP, HP superheaters. Figs. 5 and 6 are shown the most advanced triple pressure cycles which differ themselves in organisation of economisers and superheaters. Different interlining between heating surfaces of LP-economiser, IP-economiser, HP-economiser as well as between the evaporators and superheaters leads, in general, to quite different distribution on the heat consumption diagram and unexpected localisation of the pinch point.

The common assumption for all four HRSGs are as follows [4,5,19]

- Maximum HP steam superheat temperature is 535^{0}C – this corresponds to temperature of live steam used in the domestic ST of 200 MW-type.
- Minimum pinch point temperature difference is 10^{0}C.
- Minimum stack temperature: 75^{0}C.
- Maximum working pressure: 200 bar.

5 Description of the COM-GAS code

In order to perform quick and multiple calculations of combined cycle power plant during of a multi-variant design process a computer code has been developed

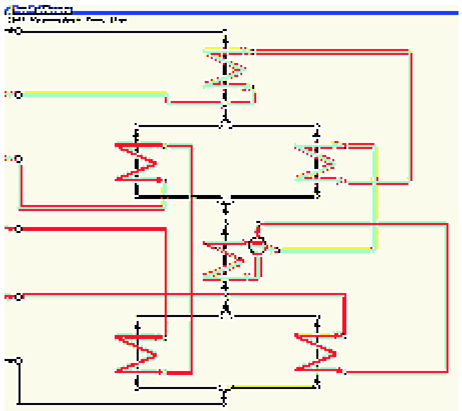

Figure 3. 1P-single pressure.

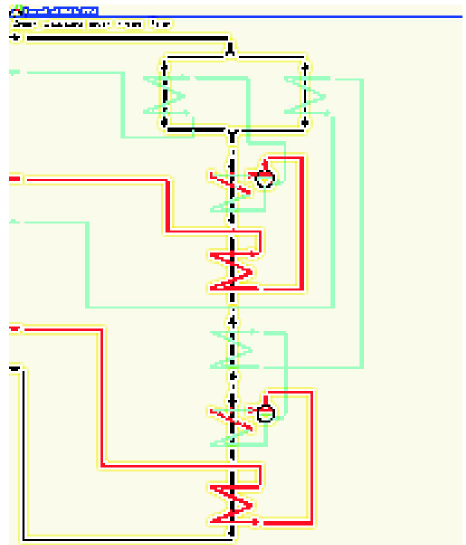

Figure 4. 2P-dual pressure.

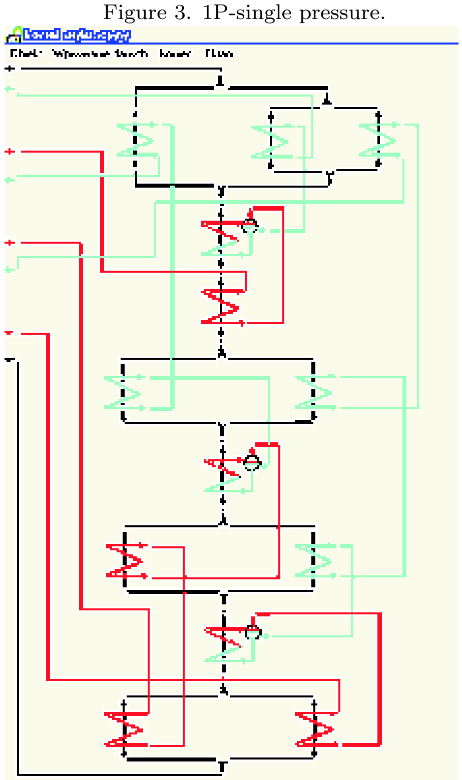

Figure 5. 3PA-triple pressure.

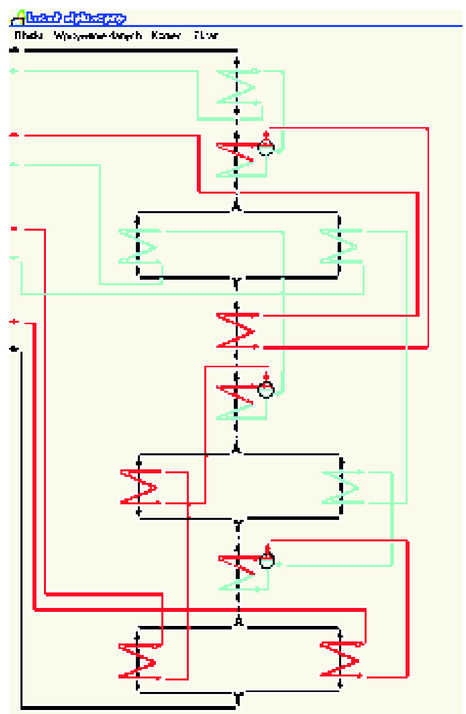

Figure 6. 3PBP-triple pressure.

combined with so-called friendly using of graphical mode for preparation and change of a scheme of cycle. The COM-GAS code algorithm is based on the fulfilment of the basic governing balances of mass, momentum and energy in the integrated version at discrete points of a cycle [13,14]. Such approach, which also has been used in other commercial codes [1-3], leads to a system of non-linear algebraic equations with unknowns such us: pressure, temperature, mass flow, mass fraction, enthalpy, etc. Discrete points are usually localised at the inlet and outlet of a single apparatus. This code, in its present form, can calculate plants that contain the following apparatus: compressors, combustion chambers, mass flow separators, pumps, ventilators, stages of gas turbines, heat exchangers (parallel- and counter flow type and parallel or sequentially arranged), feed water-tank, steam drum, coal gasificator, mass flow regulators and apparatus for total energy flow changes (heat losses, heat supplies).

Solution of the equation system is based on a sequential iteration technique that uses a linearisation into the known form; $\overleftrightarrow{A}\,\vec{X} = \vec{B}$ and the iterative refinement [17]. The range of the equation system is equal to the number of the balance points related to the number of apparatus. The vector $\vec{X}$ is the vector of unknowns that consists of either the mass flow (in the mass balance) or enthalpies (in the energy balance). The quadratic matrix $\overleftrightarrow{A}$ contains coefficients which are updated after every iteration. The vector $\vec{B}$ contains the given boundary conditions. It must be pointed out that in the COM-GAS code both $\overleftrightarrow{A}$ and $\vec{B}$ are constructed automatically from the picture of a plant, proposed on the computer screen, by a designer.

The results of calculations are visualised on a screen in such a form as it is shown, for example, in Fig. 7. Further details one can find in [15-19].

6 Parameter calculations

In order to find an optimal scheme of the combined cycle power plant the thermal efficiency of a plant should be defined. Here, knowing enthalpy of the working fluid and the efficiency η of any particular apparatus the net efficiency is calculated for every arbitrary part of the cycle according to the following procedure

$$\eta = \frac{2N_{GT26} + \sum\limits_{j=HP,IP,LP} \dot{m}_j (i_{j,steam} - i_{j,water})}{\dot{m}_{fuel} W_d}$$

where: N_{GT26} is electric output of GT26, W_d – lower heating value (LHV) of fuel.

Since certain parameters within HRSG are free and can change within technological constrains, it has been analysed efficiency of all four HRSG (e.i. 1P, 2P, 3PA, 3PB) with respect to changing enthalpy of the live steam, or the pressure

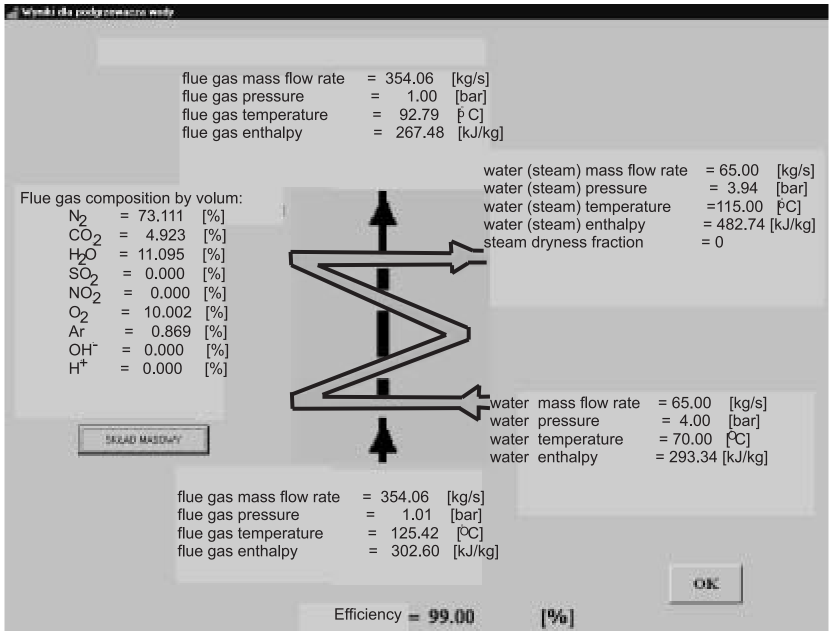

Figure 7. Typical results presentation in the Com-GAS code.

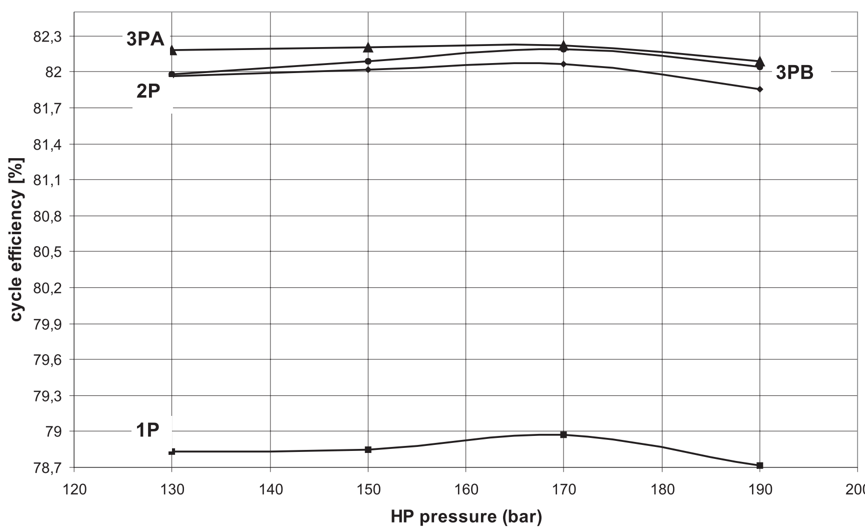

Figure 8. Efficiency of combined cycle power plant as a function of HP steam pressure.

of HP steam. Fig. 8 gathers the relevant information in terms of efficiency of combined plant about quality of the several projects. It can be seen that even single pressure HRSG, here presented for comparisons only, possesses efficiency approaching 79.0%.

7 Optimisation results

Table 2 contains the resulting data for optimal efficiency configuration calculated for 1P, 2P, 3PA and 3PB schemes, respectively.

Table 2. Combined cycle plant characteristics optimised for maximum efficiency

	1P	2P	3PA	3PB
Flue gas mass flow [kg/s]	1084	1084	1084	1084
HP pressure [bar]	170.99	170.99	169.28	170.99
IP pressure [bar]	29.4	29.11	28.53	28.82
LP pressure [bar]	–	–	3.82	3.82
HP superheat T [^{0}C]	535	535	535	535
IP superheat T [^{0}C]	535	290	535	535
LP superheat T [^{0}C]	–	–	200	200
Stack temperature [^{0}C]	112.47	79.28	77.43	77.84
HRSG power [MW]	536.0	576.3	578.4	577.9
Net efficiency [%]	78.97	82.06	82.22	82.19

From calculations of the 3PA, it follows that the inter-linking is necessary in all three stages to achieve similar temperature levels on the cooling medium side. This results in HP economiser heating surfaces being split into three separate sections. As follows from Fig. 9, that such splitting is necessary for optimal temperature distribution both on the flue gas side and on the cooling medium side.

8 Conclusion

Traditional HRSG design is essentially based on manufacturer experience and heuristics in order to obtain convenient matching of temperatures drop, pressure drop and the exchange surface area. Taking advantage of the fact that HRSG is thermodynamically determined by the knowledge of working fluid temperature and its enthalpies, it is possible, using a computer code like the COM-GAS, to find more optimal and consistent exchangers arrangement. The present study that is some kind of optimisation analysis has shown that in the case of 3PA the exchangers arrangement is not to far from optimum.

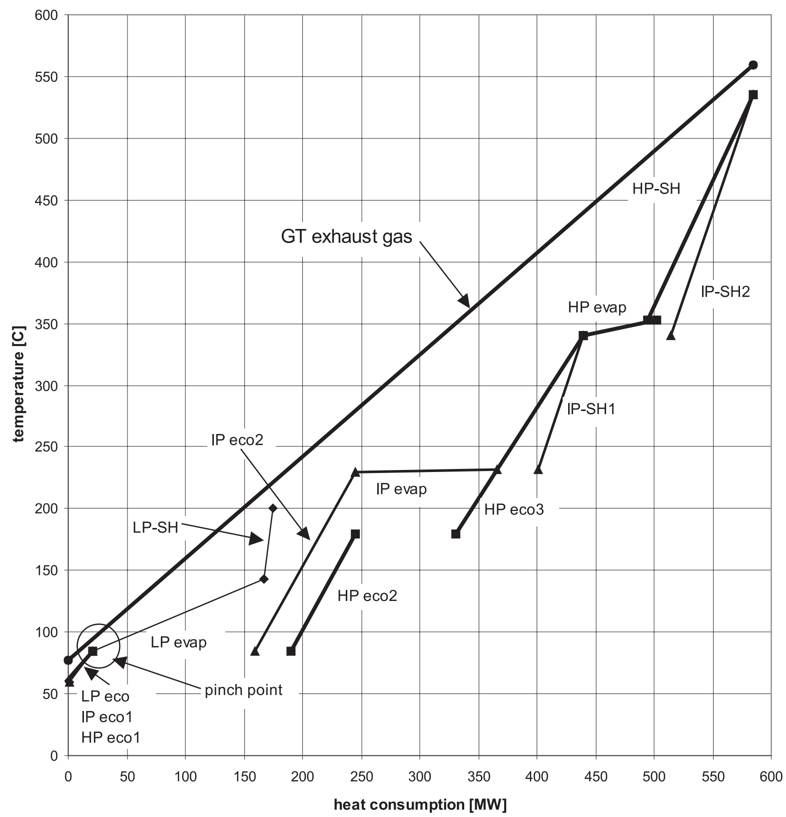

Figure 9. Heat consumption versus temperature diagram for 3PA HRSG at the point of maximum effciency.

It has to be noted that the COM-GAS code, having an open form, could be developed to a procedure for identifying temperature pinches in critical zones. In contrast to power boiler plants HRSG feature is occurring one or several temperature pinches. An in-deep reconsideration of the optimisation process is needed due to the fact that there can be contradiction between optimum of individual components of the HRSG and its overall efficiency.

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