Thermodynamic analysis of engineering solutions aimed at raising the efficiency of integrated gasification combined cycle

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Abstract. Raising the efficiency and environmental friendliness of electric power generation from coal is the aim of numerous research groups today. The traditional approach based on the steam power cycle has reached its efficiency limit, prompted by materials development and maneuverability performance. The rival approach based on the combined cycle is also drawing nearer to its efficiency limit. However, there is a reserve for efficiency increase of the integrated gasification combined cycle, which has the energy efficiency at the level of modern steam-turbine power units. The limit of increase in efficiency is the efficiency of NGCC. One of the main problems of the IGCC is higher costs of receiving and preparing fuel gas for GTU. It would be reasonable to decrease the necessary amount of fuel gas in the power unit to minimize the costs. The effect can be reached by raising of the heat value of fuel gas, its heat content and the heat content of cycle air. On the example of the process flowsheet of the IGCC with a power of 500 MW, running on Kuznetsk bituminous coal, by means of software Thermoflex, the influence of the developed technical solutions on the efficiency of the power plant is considered. It is received that rise in steam-air blast temperature to 900°C leads to an increase in conversion efficiency up to 84.2%. An increase in temperature levels of fuel gas clean-up to 900°C leads to an increase in the IGCC efficiency gross/net by 3.42%. Cycle air heating reduces the need for fuel gas by 40% and raises the IGCC efficiency gross/net by 0.85-1.22%. The offered solutions for IGCC allow to exceed net efficiency of analogous plants by 1.8-2.3%.

1. Introduction

The combined gas-steam cycle of Brayton and Rankine approaches in the efficiency to its temperature maximum of ~1700°C [1]. However, cycle efficiency in this case depends on the fuel type more than in the conventional steam-turbine cycle. According to DOE-NETL [2], operating IGCC on the basis of the oxygen gasifier and cold fuel gas clean-up (CGCU) fall behind those, that operate on ready-made standard fuel, by 10-12%. The difference is less significant in air-blown IGCC [3]. According to MHI [4], the difference in efficiency between IGCC with air gasification and cold fuel gas clean-up and NGCC amounts to ~10%.

The potential of the modern air-blown IGCC is not fully realized. The reason for this is the operation of 'gasification island', which is less effective than the operation on oxygen. This is connected with the higher ballast nitrogen content in syngas. The main factors that determine the potential of the air-blown IGCC using are as follows:

- The cold gas efficiency of coal conversion is 65-75% as opposed to 80-84% for oxygen-blown IGCC;
- The heat value of the received gas is 4-4,5 MJ/m^3 as opposed to 10-12 MJ/m^3;
- A smaller degree of binarity of the plant due to a greater expenditure of high-pressure steam from the syngas cooler to the steam-power cycle of the IGCC;
- A greater materials consumption in the systems on the gasification island under higher pressure;
- Considerable costs for the booster compressor drive.

One obvious benefit of using an IGCC is the fact that, irrespective of the fuel conversion type, the operation of integrated gasification combined cycles (either air-blown or oxygen-blown), is characterized by increased environmental friendliness. This is conditioned by the usage of effective clean-up systems for syngas before combustion [5] and unified technological solutions for syngas preparing for low-emission combustion [6].

2. Research methods

2.1. Process flowsheet of IGCC

The basis for creation of the studied flowchart of the IGCC is the combined cycle of utilization type, which is built on by the equipment for receiving and conditioning of syngas (Fig.1). The power plant flow diagram has been modified in comparison with the flowchart for natural gas. Air for the gasification process is selected from the GTU cyclic compressor. Complete integration of technological and power parts for blast air enables us to reject the modification of the GTU compressor, while retaining the flow rate of the working medium, which corresponds to operations condition for natural gas.
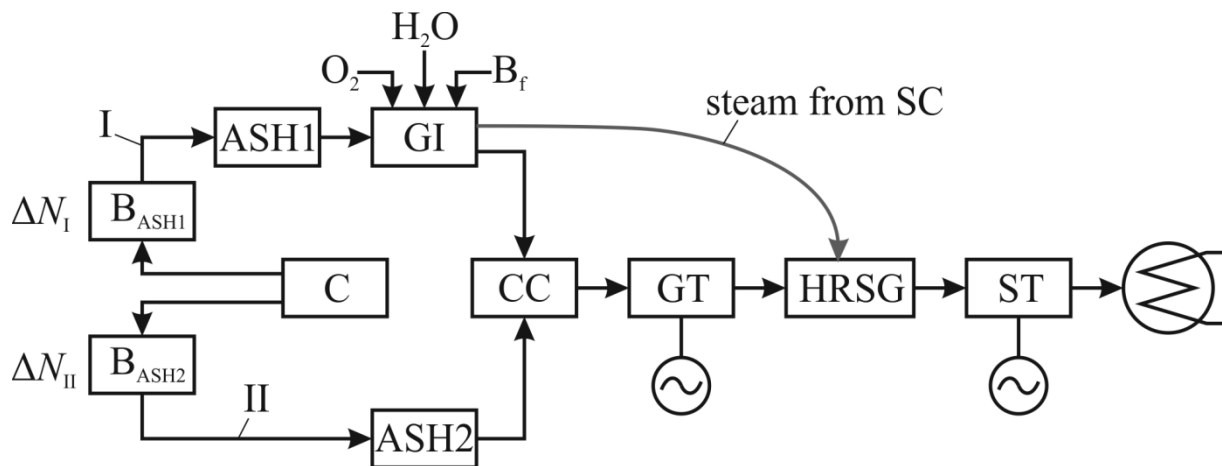
Figure 1. IGCC structural flowchart
CC– cycle compressor; BC– booster compressor; ASH – air-steam heater; CC – combustion chamber; GI - gasifier island switches in the gasifier, syngas cooler and gas clean-up; SC –syngas cooler; B$_f$ – fuel consumption (coal); FW – feed water

The gasifier is an air-blown entrained-flow reactor with slag-tap removal. The analog is the two-stage gasifier of Mitsubishi Hitachi Power Systems (MHPS) [7]. The gasifier operates on the pulverized Kuznetsk bituminous coal (flame coal) of standard grind. As compared to the analog, the gasifier underwent changes in design characteristics and operating parameters: blast air temperature was raised up to 900°C; a part of the coal fed in the second stage was replaced with water steam (0.05 kg steam/kg fuel), the cooled after the compressor air is carrier gas of pulverized coal. All this results in an increase in the oxygen output and oxygen/CO ratio, as well as in the syngas heat value, that

carries to increase in the gas turbine capacity, facilitates suppression of fuel nitrogen oxides generation; it also stabilizes the combustion process in the gas turbine combustion chamber.

The design of the syngas cooler is convection type with two pressure contours, operating in vaporizing mode.

Gas clean-up is considered two types – hot catalytic fuel gas clean-up (with process temperature ranges of 500-550°C and 900-1000°C) and cold fuel gas clean-up (which includes syngas cooling from 350 to 150°C in a wet scrubber and MDEA elimination of H_2S at 30°C).

Air-steam heaters (ASH) 1 and 2 are devices for high-temperature heat-up of air-steam blast and cycle air with pulverized-coal furnace and convection heat-up sections, whose characteristics were borrowed from [8]. There is the suptechnoerheater coil in the air-steam heater. Air-steam heaters operate on pulverized Kuznetsk bituminous coal (flame coal).

The power part of IGCC is built on the basis of Mitsubishi 701F GTU, which works jointly with a three-circuit heat recovery steam generator (HRSG) and a condensing steam turbine. The modifications of this GTU have well proved during the work on poor industrial gases. The HSRG is integrated into the engineering design through feed water–steam connections by feed water bleeding after economizers and recovering dry-saturated steam from the syngas cooler and gasifier membranes wall. With account of the latter HRSG design undergoes modifications, reducing the total area of the boiler evaporation surfaces and increasing of the steam superheating area.

The steam-turbine plant is built similarly to CCP SST-5000, developed by Siemens. The modifications of a steam turbine plant come down to increasing flow sections of pipelines and the turbine blades height of the air-gas channel due to an increased mass flow of water steam, as well as the condensing system capacity.

The parameters of the chosen power equipment were tested during the work on natural gas in the environment conditions, corresponding to ISO, and were borrowed from [9].

2.2 Calculations

The research of the work of the technological scheme is conducted by varying a number of input and intermediate parameters: gas clean-up temperature t_{GC} (30, 500 or 900°C), cycle air temperature t_{CA} (500 or 900°C) and steam-air blast temperature t_{SAB} (500 or 900°C).

Thermodynamic calculations are executed by means of Thermoflow software developed by Thermoflow Inc. The calculation methods for the gasifier were tested on an oxygen-blown gasifier of Shell type and air-blown gasifier developed by MHI. The calculation methods for the heat chart were tested on an IGCC Buggenum [10, 11, 12]. The discrepancy between design values and actual equipment performance does not exceed 2.5%.

3. Research results for an IGCC **with warm gas clean-up**

Let's study the operation of the IGCC with warm gas clean-up, which follows the calculated trajectory $(t_{GC}/t_{CA}/t_{ASB})$ 500/500/500°C, 500/500/900°C, 500/900/500°C, 500/900/900°C.

3.1. Analysis of energy efficiency of GTU as part of IGCC

With constant gas turbine input values, which determine the expansion work - temperature, composition and true mass flow of the working medium, the output and efficiency of a GTU will depend on the loading on fuel and oxidizer preparation systems.

When working on natural gas, its flow is negligible; main loading on working medium preparation is undertaken by the cycle compressor, which feeds compressed air into the combustion chamber. (link I on Fig.1). With a shift to syngas of in-cycle gasification, the system of in-cycle syngas generation (gasifier island) is introduced into the preparation system of the working medium GTU, which has a considerable storage capacity and high hydraulic resistance $\Delta P \sim 1\text{-}1.5$ MPa.

It is possible to unload the unit of the gasifier island if the qualitative adjectives is improved (through increasing the cold gas efficiency of syngas receiving process) and/or a partial exclusion of the unit from the preparation system of GTU air-fuel mixture. To unload the unit, it is necessary to

introduce additional heat energy to the gasifier (with superheated blast air and water steam) and the combustion chamber (with superheated cycle air) as well as through the transfer from cold fuel gas clean-up to hot fuel gas clean-up. The hydraulic resistance of additional heating devices – 'air boilers' ASH1 and ASH2 is relatively small ($\Delta P \sim 0.05$ MPa), which testifies to energy efficiency of the substitution equipment.

In the heat flow diagram with the gasifier island fully integrated with GTU (as the most efficient one), connecting GI, ASH1 and ASH2 means changing link I to links II and III (Fig.1)

When a gas turbine operates on syngas along the trajectory 500/500/500 °C, the power output and GTU gross efficiency values will be 276 MW and 33,37% as opposed to 312 MW and 39,5% for the operation on natural gas.

With a steam-air blast temperature increase the content of blast air in fuel gas decreases, while syngas heat value and the cold gas efficiency of gasification increase. Raising of steam-air blast temperature to 900°C (trajectory 500/500/900°C) will also raise GTU power to 278 MW and the efficiency to 34%. Heating of cycle air up to 900°C (trajectory 500/500/900°C) will decrease the load on the booster compressor and will result in an increase in GTU power to 280 MW and in the efficiency to 35.88%. The difference in values between the operation modes – on natural gas and on in-cycle gasification products will be 32MW in power and 3.6% in efficiency. This effect is conditioned by decreasing the load on the booster compressor as well as by increasing the excess air factor in the combustion chamber, and by approximating the working medium by composition to the clean air with corresponding changes of thermophysical properties and exhaust gases temperature decrease (Fig. 2a). Efficient work of the air-steam heater will start when cycle air temperature reaches 600-750°C.
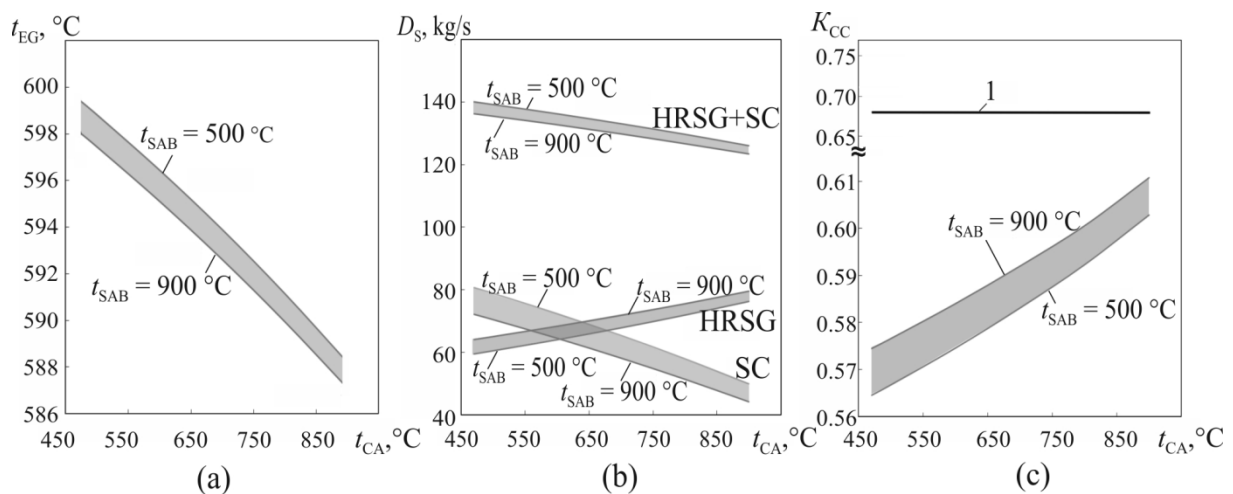
Figure 2. The relationship between GTU exhaust gases temperature (a), the efficiency of steam-generating surfaces (b) and K_{CC} (c) and the temperature of steam-air blast and cycle air: 1 – GTU performance on natural gas

3.2. Steam-power cycle analysis
Steam generation in IGCC is determined by the efficiency of heat recovery steam generator (HRSG) with an integrated syngas cooler (SC). Steam generation of HRSG itself in its initial state is 56% of the value when the system operates on natural gas (due to low heat content of exhaust gases); then it increases to 78% as their composition approaches the clean air composition.

Steam capacity of the syngas cooler is tightly connected with the flow of syngas; it decreases as blast and cycle air temperatures increase.

The total steam capacity of IGCC, which in its initial mode exceeds NGCC steam generation by 40%, will decrease due to an increase in the temperature factor (Fig. 2b)

Decreasing steam flow with constant temperature of initial and intermediate superheat will lead to a decrease in steam turbine capacity. As a result, when the temperature factor increases, the ratio of gas and steam turbine power output characterized as K_{CC} (Fig.2c) will approach the ratio of same values for the operation of natural gas.

3.3. Energy performance analysis for IGCC
In its initial state (trajectory 500/500/500°C), IGCC power amounts to 483/468 MW gross to net, exceeding natural gas performance values by 20–30 MW (Fig. 3a). Connecting ASH1 to the gasifier island system and increasing steam-air blast temperature to 900°C (trajectory 500/500/900°C) will decrease IGCC power by 1%. Increasing cycle air temperature in ASH2 to 900°C (trajectory 500/500/900°C) will decrease the power values of the power unit to 458/445 MW gross to net. The reason for a IGCC power output decrease is decreasing the fuel flow and unloading the steam turbine part.
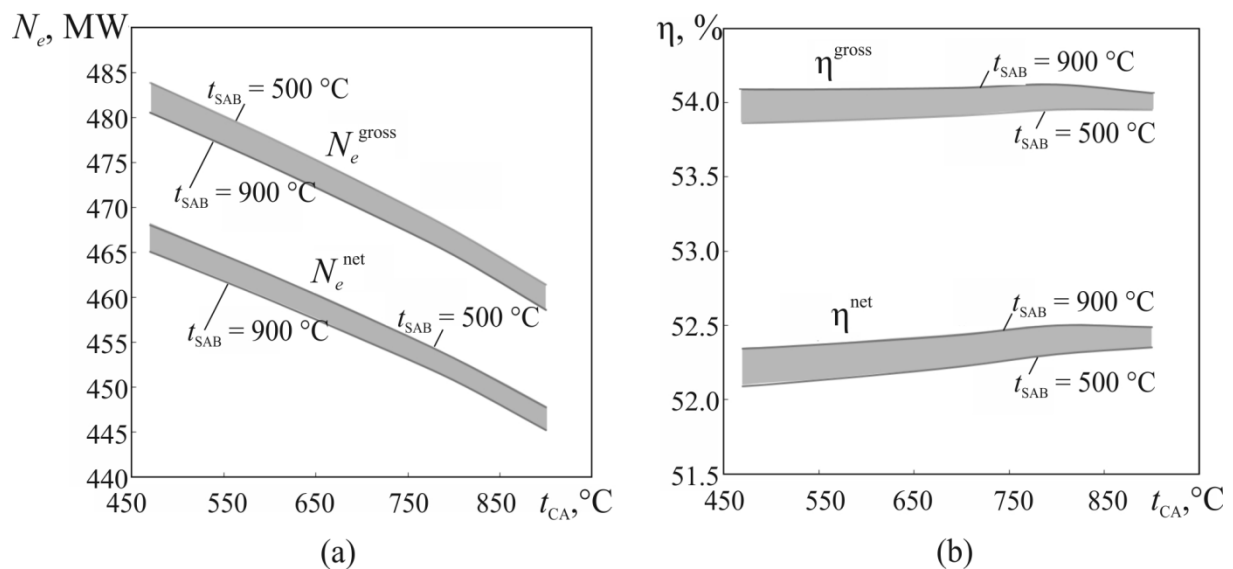
Figure 3. The relationship between IGCC power output gross to net (a), IGCC efficiency gross to net (b) and the temperature of steam-air blast and cycle air

A simultaneous temperature increase of steam-air blast and cycle air to 900°C has a very weak effect on the gross/net efficiency (Fig.3b). However, primary fuel (coal) flow in the gasifier island decreases from 39.8 to 24.7 kg/sec, i.e. by 38%, which gives us a 38% unload of the gasifier island system when it operates as part of the IGCC suggested. The coal saved in the gasifier island is transferred to ASH2 in corpore (about 15 kg/sec).

4. The influence of gas clean-up temperature on IGCC efficiency
The maximum gross power output of IGCC corresponds to the values of the cold fuel gas clean-up mode without heating the air blast (trajectory 30/500/500°C) and equals 510MW. A transfer to the warm gas clean-up (500/500/500°C) will reduce IGCC power generation to 483 MW or by 5.3%. Increasing clean-up temperature to 900°C (900/500/500°C) will decrease the power generation to 450 MW. Increasing cycle air temperature (900/900/500°C) will lead to a power output decrease by 13 MW. Heating air blast to 900°C (900/900/900°C) will lead to a power output decrease by 5 MW.

The effect of IGCC power output reduction is connected with the gasifier island unloading due to hot syngas heating value growth. will simultaneously decrease from 166-90.6 kg/s to 136-73.7 kg/s, depending on steam-air blast and cycle air temperature. Steam generation of the fuel gas cooler will decrease proportionally to the gas mass-flow from 122-67 kg/sec to 27.5-14.9 kg/sec. When cold fuel

gas clean-up system is used, steam generation of the syngas cooler is 4 times higher than that of HRSG. The total steam flow decreases with a syngas clean-up temperature increase from 157kg/s (cold fuel gas clean-up without heating air blast and cycle air mode) to 102kg/s at 900/900/900°C mode. The influence of the syngas cooler on the total steam generation will fall from 77 to 14%. ST power output will decrease from 237 to 151MW, which will increase K_{CC} from 0.535 to 0.653 with slight changes in GTU generation (280±7 MW).

The gross/net efficiency of IGCC grows with an increase of gas clean-up temperature due to a reduction in the coal flow, which is caused by fuel gas heating value increase. There is a well-known [10] gross/net efficiency surge (~3-4%), when the transfer from cold to warm fuel gas clean-up is made. A gas clean-up temperature increase to 900°C raises the gross/net efficiency only slightly (by 0.5%). Heating air blast to 900°C in combination with unheated cycle air and cold fuel gas clean-up leads to net efficiency increase by 0.42%. When the transfer to warm fuel gas clean-up is made under these conditions, the increase goes down to the value 0.3%. With a further gas clean-up temperature increase to 900°C, the net efficiency does not display any noticeable growth, whereas the gross efficiency reaches its maximum of 54.72%. When cycle air temperature reaches 900°C, the effect of blast air heating is ambiguous: the efficiency grows by 1.22% with cold fuel gas clean-up, remains unchanged with warm fuel gas clean-up, and goes down by 0.85% with hot fuel gas clean-up.

5. Comparison with counterparts

IGCC technologies with oxygen blow, with wet (in compliance with GE technology) and dry (in compliance with Shell technology) fuel feed were chosen for referencing, together with IGCC MHI with concentrated air blast (table 1). All variants operate under compatible conditions – on Kuznetsk bituminous coal, single-type power equipment and without cycle air heating.

Table 1. Comparing the given IGCC with counterparts

Parameter	GE	Shell	MHI	UrFU	UrFU
Gas clean-up type	Cold	Cold	Cold	Cold	Worm
Cold gas efficiency, %	74.8	79.5	81.5	84.2	84.2
K_{CC}	0.572	0.579	0.566	0.594	0.611
Efficiency gross/net, %	53.2/47.5	55.4/49.7	55.2/50.2	51.8/50.1	54/52

6. Conclusion

A study of the integrated gasification combined cycle plant fueled with Kuznetsk bituminous coal and with the syngas correction using high-temperature steam-air blast, cycle air heat-up, showed a reduction of fuel gas flow by approx. 50%. A positive effect from the heaters of steam-air blast and cycle air is observed from ~750°C.

Increasing the temperature of steam-air blast to 900°C increases the efficiency of fuel conversion to 84,2%. Heating cycle air to 900°C before the combustion chamber results in a decreased fuel gas flow and increases air-fuel ratio by 1.65 times, the specific compression work in the cycle by 10% and a reduction of steam flow from the syngas cooler by 2 times.

Raising syngas clean-up temperature from 30°C to 500-900°C results in a decreased demand for fuel gas at the power plant and a reduction of the fuel flow in the process by 20%. The gross/net efficiency increases by 4%, which is 1.8-4.5% higher than all known counterparts.

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