Use of poor industrial gases for power generation in the combined cycle

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Abstract
The existent world experience of steam-gas installations use on poor industrial gases is considered. On the example of installations of China, Japan and Ukraine, the technical and economic efficiency of their application is shown. Classification of industrial gases and estimation of potential of poor gases is carried out. The principles of modernization of standard gas-turbine plant for burning of blast-furnace gas are described. The authors' calculation results on efficiency of blast-furnace gas burning in standard steam-gas installation relative to the Russian conditions are given.
Key words: STEAM-GAS INSTALLATION, GAS-TURBINE PLANT, BLAST-FURNACE GAS, POOR INDUSTRIAL GASES

Introduction

The prices increase of standard fuels (natural gas, diesel fuel) causes the growth of consumers interest in the use of poor gases as fuel for gas turbines. According to the forecast of the Siemens Company, the power generation quantity by the gas turbines operating on non-standard fuels (low calorific value poor and synthesis gases) in 2020 will be from 6 to 10% of the general gas turbines generation on all the types of fuel (Fig. 1). At that, the installed capability increase of gas turbines on poor gases is predicted from the level of 8 GW to 80-130 GW in 12 years [1].

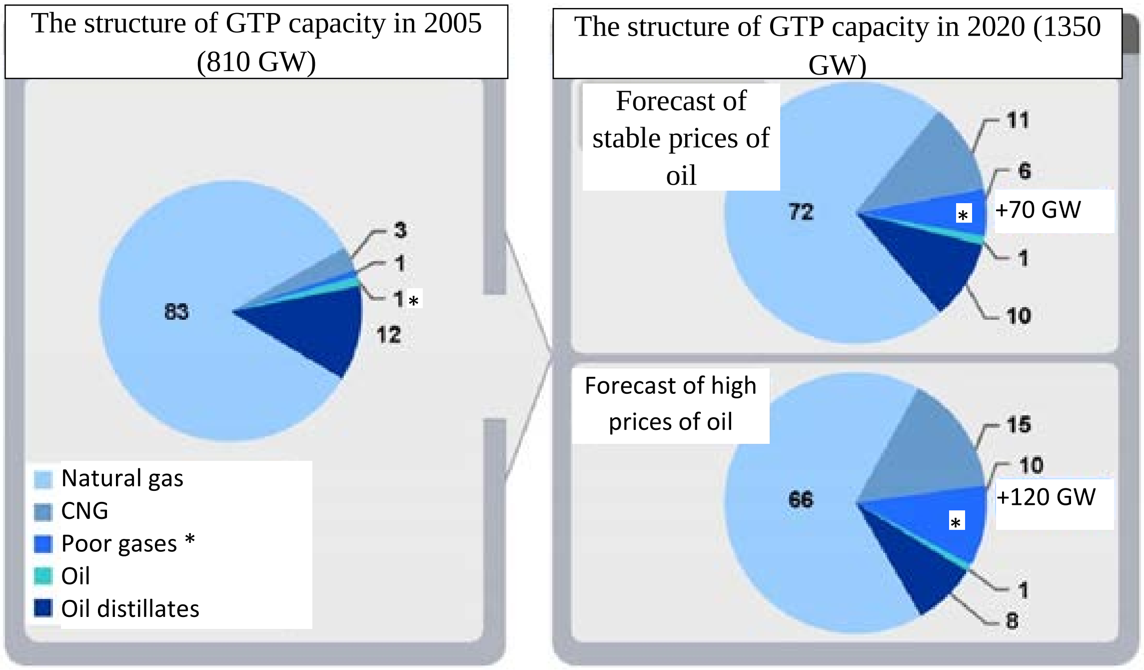


Figure 1. The forecast of structure change of the used GTP fuels

The gases, which can be divided into ready industrial gases and specially produced, are used as non-standard gases for GTP.

Ready industrial gases are blast-furnace gas (dust-free) - BFG, coke oven gas - COG (purified of dust and tar), Linz-Donavitts gas, which is converter on technology - LDG, gases of technologies of Finex, Corex, oil processing gases, biogases from SDW landfills.

Specially produced gases: the gases of steam-oxygen and steam-air gasification received from fossil fuel, oil waste.

By efforts of the leading developers (Siemens, GE, MHI), the unit capacity of SGI installations on artificial gases rose beyond 400 MW, and the lower bound of fuel gases according the calorific content is between 2.8 and 4 MJ/m^3 with a tendency to further decrease.

The main consumers of the power equipment on poor gases are the largest industrial enterprises of the traditional coal and metallurgical complex. The leading place among them is taken by the Chinese companies. The cluster of pure coal-fired and "green" power industry is the second large group of consumers. It is based on the intracyclic thermochemical recycling of low-grade fossil fuels and biomass into poor gas and its use in the combined steam-gas cycle.

The market of industrial combustible gases generally consists in meet of the in-house needs of metallurgical productions (Russia, Ukraine, Kazakhstan, Japan, the USA, EU countries), and also, of municipalities (China). 13 SGI with a general capacity of 2.3 GW were put into operation at the metallurgical enterprises of China from 1997 till 2006. SGI of the MHI Company operate with the general capacity of more than 2.5 GW at 18 metallurgical enterprises in Japan. Two SGI blocks with a general capacity of 303 MW on the basis of GTP MHI M701S (DA) operate at Alchevsk Metallurgical Plant (Ukraine). The mix of blast-furnace, coke-oven and converter gas is used as fuel [3].

Potential assessment of poor industrial gases

Let us estimate the potential of poor industrial gases on the example of blast-furnace gas. Data for the blast-furnace gas output assessment are obtained in accordance with smelting volumes in blast furnaces in 2013 [4].

Data on natural gas consumption volumes in 2013 are used from [5].

From the Table 1, it can be seen that the potential of poor industrial gases is significant value even in comparison with natural gas.

The use of blast-furnace gas in a steam-gas cycle will allow Ukraine to meet 100% of the in-house needs of the metallurgical complex of electric energy (estimated in [3] at 2 GW).

Table 1. Assessment of blast-furnace gas potential

	Russia	Ukraine	China
Output of blast-furnace gas in relation to natural gas: billion. m^3 / billion. m^3	75 / 190.1*	44 / 64	1000 / 194
Blast-furnace gas potential in relation to natural gas: mil. GJ / mil. GJ	220 / 6393*	128 / 1643	3119 / 5363

* - at TPP [6]

Properties of industrial gases

The main characteristics of the industrial gases, which were widely used as fuel for GTP, are given in Table 2 [7, 8].

Table 2. The main characteristics of the industrial gases

Fuel type	H_2, %	CO, %	CH_4, %	CO_2, %	N_2, %	H_2O, %	C_2H_6, %	The lowest combustion heat, MJ/nm^3	MWI
Blast-furnace gas [7]	2	23	0	20	55	-	-	3.13	2.6
Coke oven gas [7]	55	10	25	5	4		1	16.84	23.1
LDG converter gas [7]	0	65	5	10	20	-	-	10.03	8.7
Coke-oven and blast-furnace gas [7]	6	24	1.6	17	49	1,7	0,2	4.40	3.8
Finex gas [7]	15	29	2	44	9	-	-	5.95	5.0
Corex gas [7]	23	30	0.2	6	0.8	40	-	6.36	6.8
Syngase Of steam-air gasification [7]	16	18	2	10	54	0.5	-	4.69	4.4
Syngase Of steam-air gasification with removal of CO_2 [7]	29	6	0.1	3	61	0.5	-	3.93	4.0
Syngase of steam-oxygen gasification [8]	44.7	50.1	0.2	3.2	0.5	-	-	11.23	10.5
Diluted natural gas [7]	0	0	45	45	8	-	2	17.45	14.9
Natural gas [7]	0	0	92	2	2.0	-	4	35.62	39.8

MWI – modified Wobbe index

The main characteristics of non-standard fuel gases are shown in Fig. 2, 3.

Rich fuel gases have the lowest combustion heat of more than 20 MJ/nm^3. For intermediate calorific value fuel gases, the lowest combustion heat is 8-20 MJ/nm^3. Fuels with combustion heat of 2.5-8 MJ/nm^3 belong to low calorific value or poor gases.

As is seen from Fig. 2, 3, non-standard fuels for GTP differ significantly by composition, as well as by combustion heat. The combustion heat is reduced due to dilution of hydrocarbons with impurity gases (N_2, CO_2, H_2O), or due to hydrocarbons substituting with syngas components (CO and H_2). Industrial gases (Pos.3 Fig. 3) have the widest range of change of both composition and combustion heat. The richest of them (like coke oven gas) are used on the same technologies as the natural gases. It can be seen from Fig. 3; the natural gas and oil gases have identical Wobbe index, which is one of the main criteria of gaseous fuels interchangeability. The GE company uses the following definition of the modified Wobbe index in the calculations [9].

$$MWI = \frac{Q_i^d \cdot 107.66}{\sqrt{MW \cdot (T + 273.15)}}$$

wher Q_i^d – The lowest combustion heat of fuel gas, MJ/nm^3;
MW – molecular weight of fuel gas;
T – temperature of fuel gas, ^{0}C.

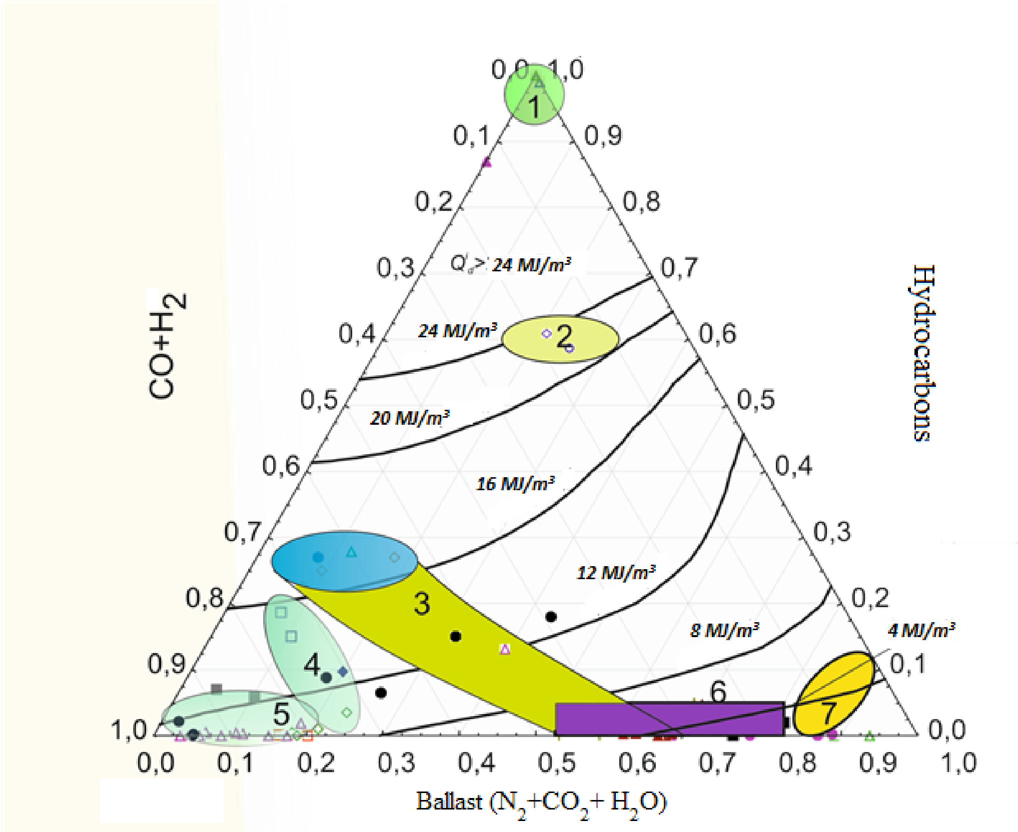


Figure 2. The composition impact on the combustion heat of fuel gases [10]
1 – natural gas; 2 – char gases; 3 - industrial gases (coke oven, blast-furnace, converter and their mixes); 4, 5 – gases of steam-oxygen gasification; 6, 7 – gases of steam-air and air gasification

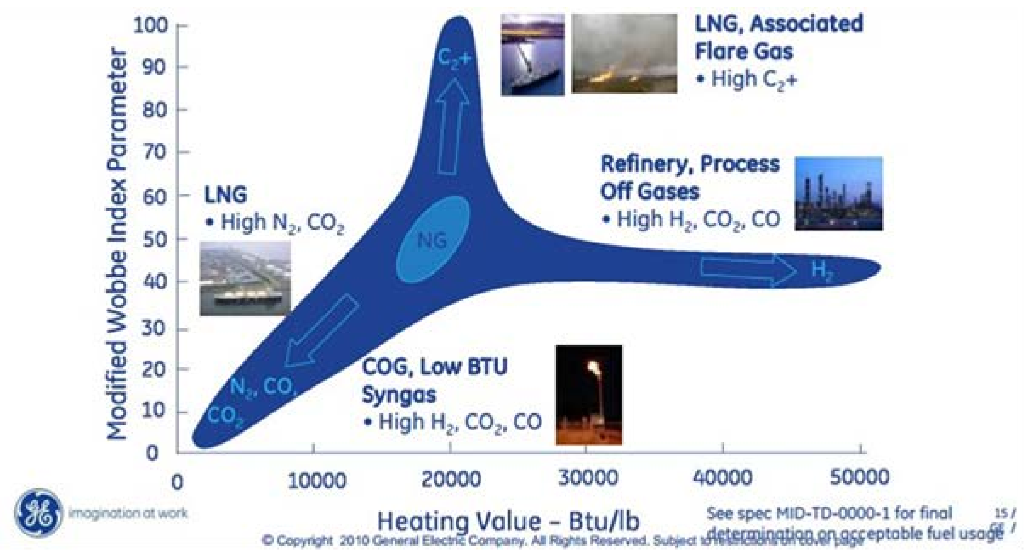


Figure 3. Characteristics of non-standard gases. NG – natural gas, LNG - liquified natural gas, COG – coke oven gas

The equipment modernization is necessary for burning of poor gases (like blast-furnace and converter gas) even at their utilization in coppers even when recovering of them in the boilers. Gases of steam-oxygen gasification (Pos. 4, 5 Fig. 2) are used with the minimum modification of the standard gas burner unit. Gases of steam-air (Pos. 6 Fig. 2) and air (Pos. 7 Fig. 2) gasification are little different from blast-furnace gas according to application method.

In Fig. 4, the dependence of air theoretical volume and flue gases volume on the fuel combustion heat is shown. It is seen that the air theoretical volume is 10-100 times less for poor gases than for natural gas. It causes the considerable change of the ratio of air and fuel flow rate in comparison with burning of natural gas and the necessity of modification introduction of fuel-using unit design at its conversion from the natural gas to industrial gas burning.

The dependence of theoretical temperature of syngases burning in the air on combustion heat at the excess air coefficient equal to 1 and 3 is presented in Fig. 5. For comparison, the characteristics of SGI with integrated gasification combined cycle (IGCC) with hot (Pos. 1, 2) and cold gas purification are given in Figure (Pos. 3). The hot syngas (500 °C) is burned in high-heated (1000 °C) cycle air In SGI with IGCC with the characteristics shown in Position 1 (Fig. 5).

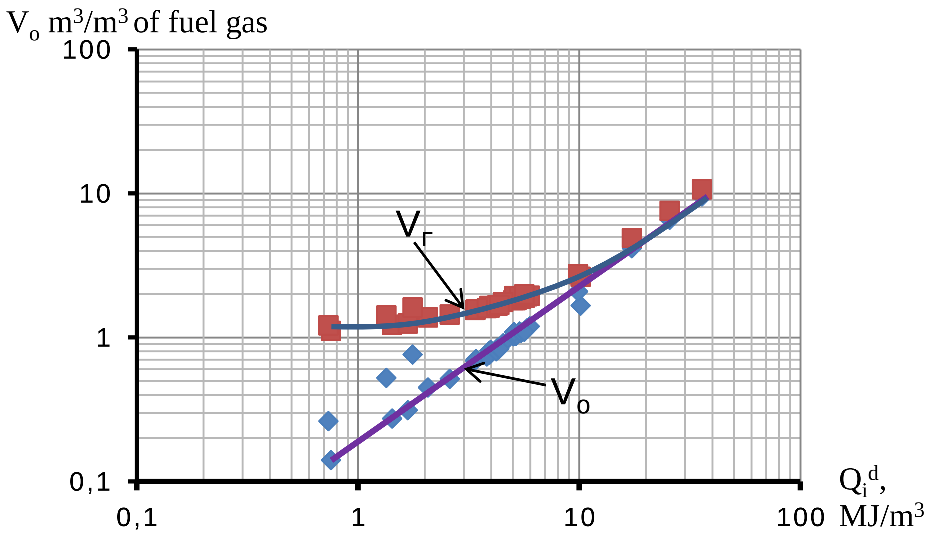


Figure 4. Dependence of air theoretical volume and flue gases volume on combustion heat of fuel

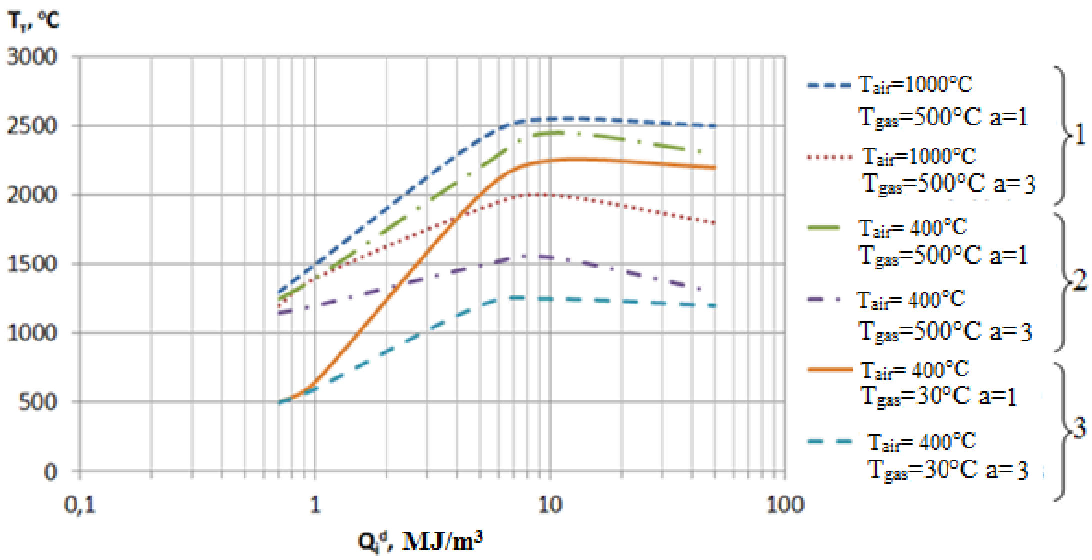


Figure 5. Theoretical temperature of artificial gases burning considering dissociation of combustion products depending on their combustion heat [12]

From figure 5 [12], it can be seen that the poor gases use for SGI simplifies the technology of ecological burning due to their low theoretical temperature of burning, and the air and gas heating before feeding in the combustion chamber will allow to provide high stability of a diffusion flame. As a result, the fuel base of long-range GTP is extended considerably due to possibility of effective operation on cheap poor artificial gases, which were not used to this purpose earlier, with $Q_i^d \approx 1.5 \div 3$ MJ/m^3 provoking a competition for the gases of steam-oxygen and steam-air gasification.

Use of poor gases in GTP and SGI

All the industrial gases before feeding in GTP need to be prepared. The general preparatory operations for all the gases are the following: extraction of dust, compression in the compressor, heating up to the necessary temperature. Individual costs of gases preparation: coke oven gas - tar removal; petro-gas – conversion of heavy hydrocarbons; generator syngas – coal preparation for burning (drying, grinding), gasification and preparation of blow (compression, oxygen plant, steam generator), cooling of gas in the gas coolers, desulphurization.

Combustible gases of industrial productions (blast-furnace, coke-oven and others) are by-product of a basis cycle and their production costs are included in the main products price. Their preparation for burning is not relatively labor-consuming, since it is usually limited to the dust cleaning, more rarely including tar removal and heating, and compression is used at GTP. Burning is carried out usually on the gas-using units placed in the enterprise territory. The low temperature of burning causes their ineffective use in steam boilers, and considering the potential, forces to consider SGI technologies.

The intracyclic conversion gases are produced in the special devices - the gas generators placed in close proximity to the electric-power installation. The costs of their production from coal are related to production of thermal and electric energy, and depending on specific conditions, it is from 50 to 70% in the house needs structure. This fact causes their ineffective use in a steam-power cycle and forces to consider exclusively highly effective technologies (SGI).

Traditional forms of use of the industrial combustible gases are Central Heating and Power (CHP) plants with η_n 30-36 % (not exceeding the coal power units of supercritical parameters). Even today, change-over to combined cycle provides the net efficiency around 51% (the actual value reached at the enterprises of Japan, China) [13]. This offers the considerable opportunities for equipment upgrade of power supply sources of the main metallurgical enterprises with developing economy. The superstructure of CHP plants of the gas turbine allows increasing of energy generation efficiency by more than 1.5 times and increasing of thermal power plant capacity by 1.5 times (when using the same steam-turbine installation). The comparison of indicators of CHP plant and SGI (on the basis of the gas turbine MHI M701S (DA)) during the operation on the coke-oven and blast-furnace gas according to MHI [14] is shown in Table 3.

Table 3. The comparison of indicators of CHP plant and SGI of MHI during the operation on the coke-oven and blast-furnace gas [14]

Parameter	CHP plant	SGI of MHI
Capacity, MW	102	153
Efficiency, %	30	45

Comparison of indicators of SGI on blast-furnace gas, SGI with intracyclic gasification of coal on poor gas and the Russian steam-operated power plant on brown coal is shown in Table 4. In can be seen that SGI efficiency on blast-furnace gas is higher than at coal SGI, and efficiency of all the SGI is much higher than at the steam-operated power plant even despite the smaller unit capacity of SGI.

Table 4. The indexes comperison of SGI on blast-furnace gas, coal SGI and steam-operated power plant

Parameter	SGI on blast-furnace gas (Anshan, China) [13]	SGI with IGCC (The project on the basis of GTP of MHI) [15]	SGI with IGCC (Nakozo, Japan) [16]	Power plant of steam-operated TPP on brown coal (Krasnoyarsk, Russia) [17]
Capacity, MW	300	480	220/450*	800
Efficiency, %	51	48	42/46*	37
Fuel gas of GTP	Coke-oven and	Steam-air syngas	Air syngas	-

	blast-furnace gas			
Combustion heat of fuel gas, MJ/nm^3	4.4	5.14	5.0	-

* - the planned SGI indicators with the gas turbine M701F.

Modernization of standard GTP (on natural gas) for blast-furnace gas burning

In paper [8], the modernization of standard GTP with change-over to the blast-furnace gas burning is considered.

The volume of GTP necessary modernization depending on the fuel combustion heat is given in the Table 5 [8].

Table 5. The volume of GTP necessary modernization depending on the fuel combustion heat [8]

GTP element	Fuel combustion heat			
	High 42-20 MJ/nm^3	Standard (natural gas) 35.6 MJ/nm^3	Intermediate 8-20 MJ/nm^3	Low 2.5-8 MJ/nm^3
	GTP element design			
Air compressor	Standard	Standard	Standard	Modernization
Combustion chamber	Standard (insignificant modernization)	Standard	Standard (insignificant modernization)	Modernization
Turbine	Standard	Standard	Standard	Standard
Fuel system	Standard (insignificant modernization)	Standard	Standard (insignificant modernization)	Modernization

From Table 5, it is seen that the significant modernization of GTP is not required when using of fuel with higher than 8 MJ/nm^3 combustion heat. And the modernization of the air compressor, combustion chamber and fuel system of the gas turbine is necessary when burning of fuels with less than 8 MJ/nm^3 combustion heat.

Comparison of schemes of burning low - and intermediate calorific value gases in SGI on blast-furnace gas and in SGI with IGCC is shown in Table 6.

Table 6. Comparison of schemes of burning low - and intermediate calorific value gases in SGI on blast-furnace gas and in SGI with IGCC

Parameter	SGI on blast-furnace gas	SGI with IGCC				
	Kimitsu [18]	Puertollano [19]	Buggenum [20]	Tampa Polk [20]	Wabash River [21]	Nakoso [20]
Year of commercial start-up	2004	1998	1998	1999	1999	2013
Gas turbine	M701F	Siemens V94.3	Siemens V94.2	GE 7FA	GE 7FA	M701DA
Combustion chamber type	Can-annular	Outside	Outside	Can-annular	Can-annular	Can-annular
Net power of SGI, MW	300	300	253	250	262	220
Temperature in the inlet of the gas turbine °C	1300	1260	1060	1220	1220	1200

Parameter	SGI on blast-furnace gas	SGI with IGCC				
	Kimitsu [18]	Puertollano [19]	Buggenum [20]	Tampa Polk [20]	Wabash River [21]	Nakoso [20]
Initial fuel	Blast-furnace gas	Mix of coal and petrocoke (ratio – 1:1)	Bituminous coal	Bituminous coal	Bituminous coal	Bituminous coal
The lowest combustion heat of fuel gas before correction, MJ/nm^3	2.96	10.03	11.12	9.67	10.31	5.2
Correction	Enrichment by coke oven gas	Dilution by nitrogen and steam	Dilution by nitrogen and steam	Dilution by nitrogen	Dilution by steam	Without correction
The lowest combustion heat of fuel gas aftercorrection, MJ/nm^3	4.4	4.36	4.46	4.5	8.25	5.2
Composition of fuel gas before correction (volume percent, %) on dry basis						
H_2	2	22.08	28.6	37.95	34.4	10.5
CO	22.4	60.51	63.5	44.06	45.3	30.5
N_2	55.2	12.46	6.3	2.38	1.9	55.5
Ar	-	1.03	-	0.88	0.6	
CO_2	20.4	3.87	1.6	14.73	15.8	2.8
CH_4	-	-	-	-	1.9	0.7
Composition of fuel gas before correction (volume percent, %) before burning						
H_2	6.05*	10.67	12.3	17.7*	27.52	10.5
CO	20.88*	29.24	24.8	20.5*	36.24	30.5
H_2O	-	4.18	19.1	-	20	-
N_2	51.02*	53.08	42	54.5*	1.52	55.5
Ar	0.01*	0.62	0.6	0.4*	0.48	-
CO_2	19.78*	1.89	0.8	6.9*	12.64	2.8
CH_4	2.02*	0.07	0	-	1.52	0.7
O_2	-	0.25	0.4	-	-	-
C_2H_6	0.24*	-	-	-	-	-

From Table 6, it is seen that SGI with IGCC with intermediate calorific value syngases of oxygen gasification use the following ways of decrease in combustion heat of syngas before feeding in the combustion chamber.

Dilution gassy syngas by nitrogen from air separation unit (ASU) in the special mixer (SGI with IGCC Puertollano (Spain)) [19].

Dilution synthesis of gas by nitrogen, and then saturation by water vapor in special installation (SGI with IGCC Buggenum (Netherlands)) [20].

Mixing of nitrogen with syngas and air directly in the combustion chamber (SGI with IGCC Tampa Polk (USA)) [20].

Correction of syngas with steam only (SGI with IGCC Wabash River (USA)) [21].

The air gasification syngas produced in SGI with IGCC Nakoso (Japan) has low combustion heat, and therefore, do not underdo correction before burning.

At Kimitsu plant (Japan), the blast-furnace gas is used as fuel. The blast-furnace gas is enriched with coke oven gas in order to regulate the burning process [18].

From the conducted analysis of the operating installations, it is seen that the companies are forced to change over to poor gas burning and to implement measures for modernization of the fuel system, the air compressor and the GTP combustion chamber in spite of the fact that during the operation on intermediate calorific value gas, only insignificant GTP modernization is required. From four SGI using intermediate calorific value gas, the caloric content of syngas is reduced practically twice on three SGI before burning and brought to the level of the blast-furnace gas enriched with the coke oven gas.

Calculation researches of blast-furnace gas burning in standard SGI

The addition of coke oven gas to the blast-furnace gas facilitates the gas turbine operation but is the disadvantage of the scheme as the coke oven gas is a standard fuel. The calculation researches in software packages "Thermoflex" and "GT PRO" were carried out in order to estimate the opportunity of long-range high capacity GTP operation on blast-furnace gas without the coke oven gas addition. Calculations are carried out for GTP as a part of the SGI scheme with capacity about 500 MW.

The turbine M701F4 of MHI, where the natural gas served as design fuel, was accepted as gas turbine installation for SGI. The temperature of combustion products at the combustion chamber inlet for the selected turbine is 1425 °C.

Calculation is performed for two options of cycle air parameters before the combustion chamber: 1) the cold one was of a temperature of 429^0C; 2) the hot one was of a temperature from 800 to 1000^0C for stable ignition. The blast-furnace gas temperature in combustion chamber inlet (after the booster compressor and gas heater) was 350^0C.

The calculation results of GTP operation at a standard temperature of air heating in natural, coke-oven and blast-furnace and blast-furnace gases and with burning of blast-furnace gas in high-heated air of a temperature of 800 and 1000 ^{0}C are given in Table 7.

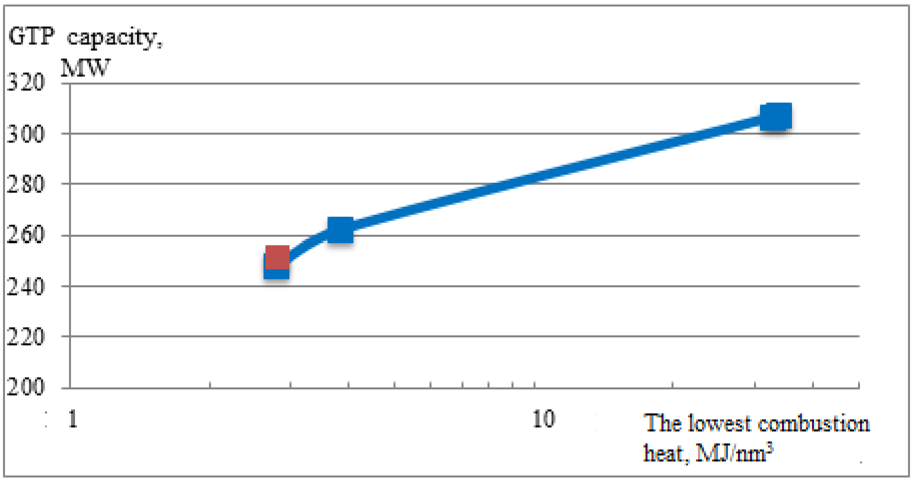
Table 7. The calculation results of GTP operation at a standard temperature of air heating in natural, coke-oven and blast-furnace and blast-furnace gases and with burning of blast-furnace gas in high-heated air of a temperature of 800 and 1000 ^{0}C

Fuel	$Q_н^p$, MJ/nm^3	Pressure in the fuel line, MPa	GTP capacity, MW	GTP efficiency, %	Air compressor capacity, MW	Fuel compressor capacity, MW	Air consumption, kg/s	Fuel consumption, kg/s	Air temperature on the inlet of CC, °C	Gases temperature on the inlet of GT, °C	Gases temperature on the outlet of GT, °C
NG	33.6	1	307.2	39.36	296.4	3.3	700.7	16.86	429.6	1400	590.1
CO and BFG	3.8	0.15	262.2	33.84	198	111.2	472.7	243.5			621.6

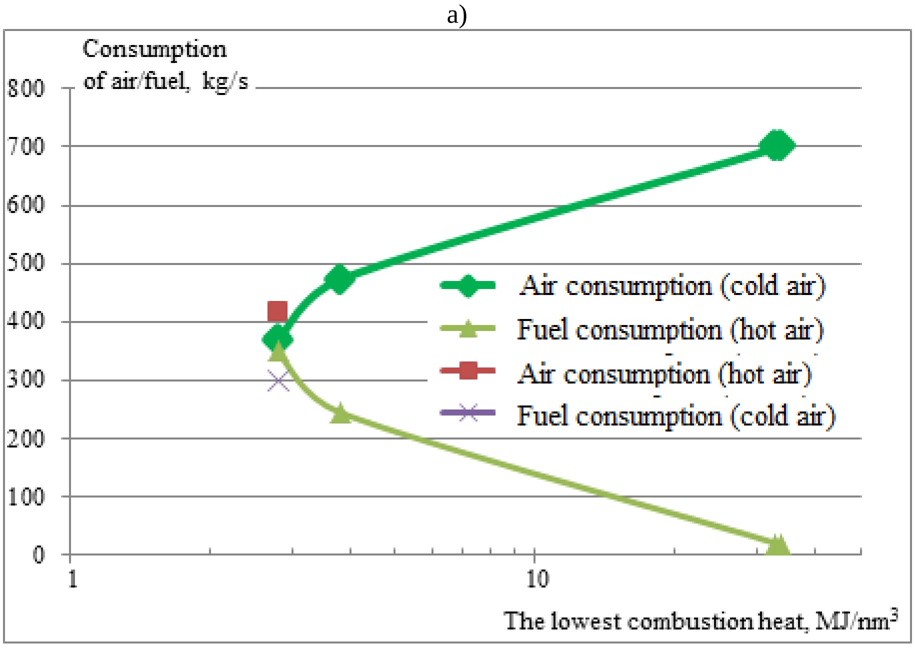
BFG, «cold air»				248.1	32.01	152.6	152.8	367.2	349.1			636.1
BFG, «hot air»	800 °C	2.8		251.8	32.92	175.5	131.2	416.4	299.9	705.8		626.5
	1000 °C			256.8	33.95	196.6	110.1	464.6	251.6	897.9		617.1

The obtained results confirm the possibility of use of blast-furnace gas in GTP M701F4. It is offered to use the air heating in order to increase the blast-furnace gas ignition stability.

The graphic dependences of change of the GTU parameters when changing over from natural gas to poor gas burning are shown in Fig. 6.



a)



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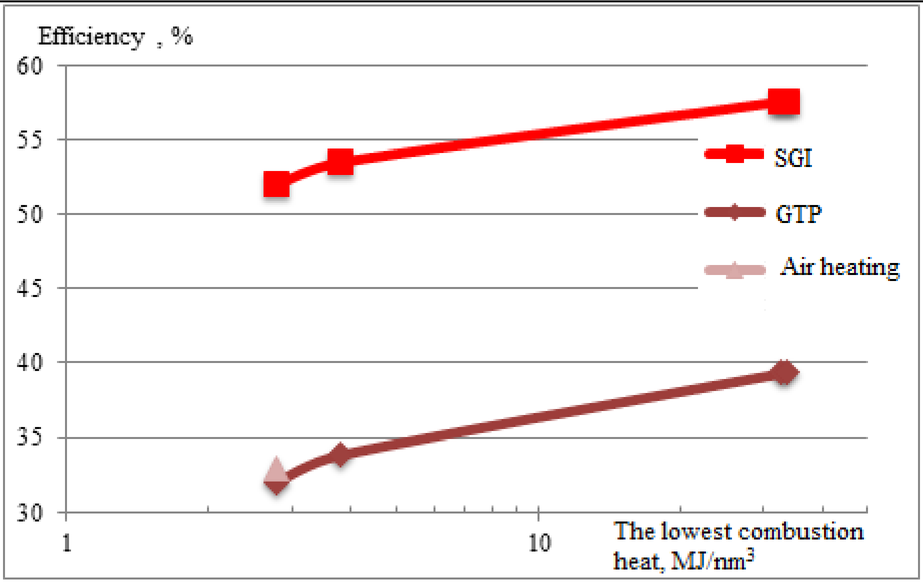

c)

Figure 6. Change of GTP characteristics depending on combustion heat of fuel.
a – capacity, b - air consumption, fuel consumption, c – efficiency. The values corresponding to the scheme of GTP on blast-furnace gas with high-temperature air heating are shown by separate point on diagrams

From Fig. 13, it is seen that change over to blast-furnace gas causes the reduction of GTP capacity by 19%, the air consumption decreases almost twice, the fuel gas consumption increases by 21 times. Decrease in efficiency of GTP and SGI is connected with various efficiency values of the GTP compressor and booster compressor of fuel gas.

The impact of air heating on SGI characteristics, when changing over to the poor gases burning, is less significant than when natural gas burning. It is explained by increase in impact of the heat brought in the combustion chamber with a fuel stream because of its quantity growth. Therefore, for considerable effect obtaining from air heating when poor gases burning, not only the temperature of air heating is important but also the temperature, to which the fuel is heated.

Economic assessment of efficiency of SGI on blast-furnace gas

Let us carry out the payback period assessment of SGI on blast-furnace gas for volumes of blast-furnace gas production of one of the largest metallurgical enterprises of Russia - Nizhniy Tagil Iron and Steel Works.

Basic data for an assessment:

The volume of production of blast-furnace gas - 5 billion m^3/year;

SGI efficiency - 52 %.

The average level of capital expenditure - 1500$/kW of installed capacity;

Electric power cost when purchasing in the wholesale market – 3.5 rub/kWh;

All the produced electric power is consumed for in-house needs.

Results:

The capacity produced by SGI on blast-furnace gas - 240 MW.

Capital expenditure for SGI with installed capacity of 250 MW – 24.4 billion rubles.

Reduction of costs of electric power purchase – 6.8 billion rub/year.

Economy of coke oven gas – 0.3 billion m^3/year.

SGI payback period – 3.6 years.

The performed assessment showed that the use of SGI on blast-furnace gas allows cutting of the enterprise costs on electric power purchase by 6.8 billion rub/year and reducing of consumption of coke oven gas by 0.3 billion m^3/year. The obtained payback period – is 3.6 years, which is 1.5-2 times lower than for thermal power plant, where the payback period of 5-7 years is normal.

Conclusion

The use of secondary fuel and energy resources for electric power generation for in-house needs is a relevant task for any metallurgical enterprise.

In this regard, the technology, which allows burning of poor blast-furnace gas without addition of high-quality fuels in an economic steam-gas cycle, is considered. The objective of this work was the efficiency assessment of technology of blast-furnace gas burning in SGI cycle and the features connected with changing over of the turbine standard gas operating on natural gas to the blast-furnace gas burning. This work relies on the well-known industrial experiment on coke-oven and blast-furnace gas burning in GTP of the leading engineering companies.

The proposed solution in combination with well-known methods will be a real basis of energy use of poor gases of various nature with refusal of special devices of flame regulation (prechamber), kinetic schemes of burning and with ensuring of environmental friendliness of burning.

The calculation researches in software packages of "Thermoflex" and "GT PRO" for SGI of capacity about 500 MW showed the possibility of burning of blast-furnace gas in long-range GTP of high capacity without addition of coke oven gas. At that, the GTP modernization caused by change of fuel gas and air volumes is required. It is offered to heat up the air before feeding in the combustion chamber for more stable ignition of blast-furnace gas.

The conducted economic assessment on the example of the large metallurgical enterprise showed that the use of SGI on blast-furnace gas allows cutting of the enterprise costs on electric energy purchase by 6.8 billion rub/year and reducing of consumption of coke oven gas by 0.3 billion m3/year. . The obtained payback period – is 3.6 years, which is 1.5-2 times lower than for thermal power plant, where the payback period of 5-7 years is normal.

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