Modernization of air-blown entrained-flow two-stage bituminous coal IGCC gasifier

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Abstract: High efficiency of combined cycle and availability of deep gas cleaning systems make it possible to consider integrated gasification combined cycle (IGCC) as promising solution for improving efficiency and environmental friendliness of coal energy. Key element of this plant is gasifier of solid fuels. Only commercial air-blown entrained-flow gasifier is two-stage Mitsubishi Heavy Industries 1700 t/d unit. Therefore, it was chosen as initial design of further modernization. Modernization purpose is increasing of gasifier efficiency and syngas H_2/CO ratio control to improve environmental performance of syngas burning in combustion chamber of IGCC gas turbine. Modernization consisted in an additional air blast heating to 900°C by high temperature air heater and steam (900°C) supplying in gasifier second stage. Determination of influence of proposed modernization on gasifier characteristics and optimization of its operating parameters were performed by carrying out multivariate calculations by zero-dimensional, one-dimensional and three-dimensional (computational fluid dynamics) models. Gasifier modernization has improved syngas thermal capacity and cold gas efficiency from 77.2% to 84.9%, and increases H_2/CO from 0.344 to 0.602. The IGCC efficiency was increased from 48 to 50-52%.

Key words: gasification, IGCC, coal, CFD, modeling

1. Introduction

Integrated gasification combined cycle (IGCC) is advanced solution to improve efficiency and environmental friendliness of coal power engineering [1]. Key element of this plant is gasifier of solid fuels (coal, petcoke, biomass in mixture with fossil fuels, etc.). According to gasifying agent, gasifiers are divided into oxygen-blown and air-blown units. Advantage of first is high cold gas efficiency, and second - low capital and operating costs [2]. In this paper, we consider issue of modernization (improving) of air-blown entrained-flow two-stage bituminous coal IGCC gasifier.

The only commercial air-blown entrained-flow gasifier is a two-stage Mitsubishi Heavy Industries (MHI) 1700 t/d unit [3]. Two-stage gasification process organization allows zoning of its main phases (combustion and gasification), which leads to increase of cold gas efficiency and carbon conversion rate. Therefore, it was chosen as initial design of further modernization.

The modernization purpose is increasing of gasifier efficiency and syngas H_2/CO ratio control to improve the environmental performance of the syngas burning in the combustion chamber of the IGCC gas turbine.

The modernization consists of several principal technical solutions:

1) steam supply to second stage;
2) additional heating of blast air.

With increasing hydrogen content relative to CO in syngas, amount of fuel nitrogen oxides formed during combustion in combustion chamber decreases [4]. To increase proportion of hydrogen in syngas, steam is added to gasifier second stage. Additional heating of blast air provides heat necessary for steam gasification. This makes it possible to optimize syngas composition for hydrogen, to increase carbon conversion rate and cold gas efficiency of the gasifier to level of oxygen gasifiers.

2. Zero-dimensional modeling

2.1. Model description

Zero-dimensional thermodynamic models are most common among mathematical models. They do not take into account type and power of gasifier, stratification of temperature and individual components in its volume, as well as time constraints that prevent the reaction system from reaching the equilibrium state. Despite large number of assumptions, such models allow to trace influence of process parameters on its performance and to identify most attractive ranges of conditions.

Analysis of air-steam gasification cases was carried out using thermodynamic model [5], without introducing macrokinetic constraints on yield of nonequilibrium gasification products. Gasification of Kuznetskiy coal was modeled. Fuel characteristics are given in Table 1. Initial parameters of model include composition and temperatures of material flows entering gasifier, as well as heat loss to environment (Table 2). Values of undefined parameters vary according to ranges specified for them. To reduce number of such parameters to two, equivalence ratio is assumed to be derived and dependent on heat exchange of gasifier with environment. This parameter is calculated, so that case is on carbon boundary line. This method allows us to find set of cases with maximum efficiency achievable for certain level of heat exchange between gasifier and environment [6].

Table 1. Kuznetskiy coal characteristics

Parameters, %	W^a	A^d	V^d	C^{daf}	H^{daf}	N^{daf}	S^{daf}	O^{daf}	Heating value, MJ/kg
Value	2.9	23.7	29.9	78.79	5.97	2.16	0.97	12.11	31.6

Table 2. Initial parameters of the model

Description	Value
Stoichiometric factor (α)	Optimized
Steam consumption mol/mol C	0 – 0.6
Heat loss, % of heating value	2
Air-steam mixture temperature, °C	500 – 1200
Fuel temperature, °C	25
Pressure, MPa	3

2.2. Modeling results

Results of calculation are shown in Fig. 1a. As can be seen from figure, cold gas efficiency of air gasification cases with zero steam consumption is slightly dependent on temperature of heated air and is in range of 80.8-83.4%. Thus, heating of purely air gasification agent does not make sense for efficiency improvement. Addition of steam makes reaction system more sensitive to gasification agent heating. Maximum cold gas efficiency, thermodynamically achievable with optimum equivalence ratio and air heated to 1200 °C and steam consumption of 0.6 mol/mol carbon, is 94.7%. However, under these conditions, resistance of recuperative heater materials is low, and reaction temperature is 895 °C. At given temperature, chemical system may be affected by kinetic limitations on completeness of fuel conversion. Reducing degree of fuel conversion will lead to increase in actual equivalence ratio and excessive oxidation of syngas combustible components.

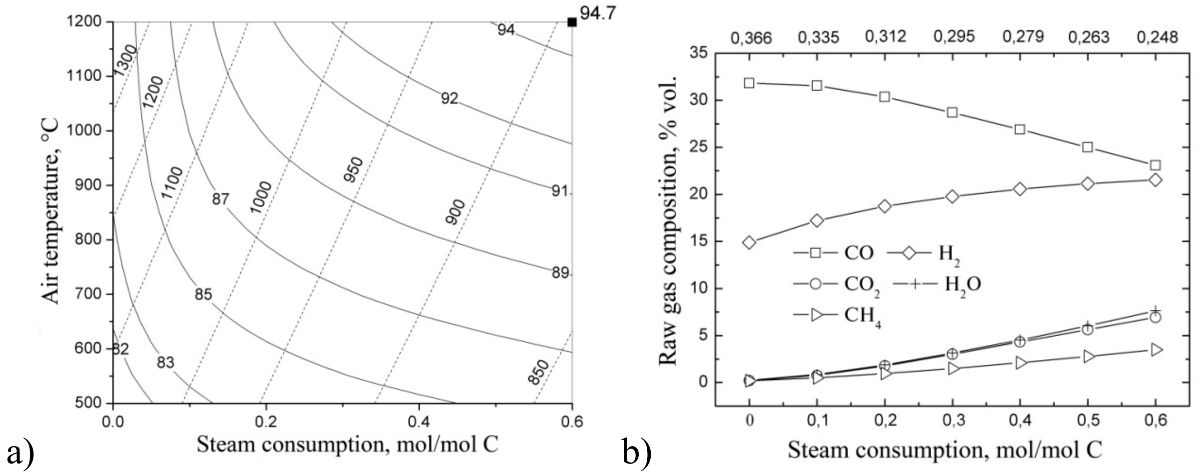


Figure 1. Influence of steam supply on gasifier operation: a) cold gas efficiency (solid lines), temperature (dotted line); b) raw syngas composition (temperature of air-steam mixture is 900 °C)

Fig. 1b shows effect of steam consumption on syngas composition at air-steam mixture temperature of 900 °C. Adding steam to air allows replacing some of oxygen in air and helps to reduce optimal equivalence ratio. At the same time, increase in proportion of steam in the mixture leads to increase in concentration of carbon dioxide and hydrogen, and also to decrease in concentration of carbon monoxide in accordance with shift reaction (1). Kinetic constraints will also appear near carbon boundary line, when decrease in reaction rate between coke and gas is due to decrease in thermodynamic potentials difference.

$$CO+H2O = CO2 + H2 \tag{1}$$

Optimal (from thermodynamic point of view) cases were used as the starting points for further one-dimensional modeling (blast air temperature of 900°C, gasifier outlet temperature of 1100°C, steam consumption less than 0.1 steam mole / carbon mole). Increasing dimensionality of model and its detailing leads to increase in number of process parameters and possible design modes. Also, computational resources expended on calculation of each of modes are significantly increased. Use of optimal thermodynamic cases as initial variants in one-dimensional modeling makes it possible to substantially reduce number of design options, as well as to justify their choice.

3. One-dimensional modeling

3.1. Model description

Thermodynamic analysis allows identifying number of regimes that can be efficient in achieving equilibrium in gas-fuel system. For more precise estimation of regimes efficiency it is necessary to take into account macrokinetic constraints existing in this system. Before proceeding to CFD calculations (that are most expensive from computational point of view) it is advisable to conduct additional selection of gasification regimes using simplified one-dimensional model of the gasification process (reduced order modelling [7, 8]).

Presence of feedback in staged scheme can lead to new qualitative features of coupled operation of two gasifiers in comparison with the one-stage process. At low degrees of secondary fuel conversion degree, coke-ash residue formed at the outlet is cooled and sent back to the combustion gasifier. It leads to an increase in heat losses and to regular decrease in first stage fuel conversion degree. In order to avoid accumulation of circulating ash, it is assumed in calculation that the entire solid residue at the first stage is carried away with liquid slag. Then regimes in which temperature required by liquid slag removal condition is not reached become inefficient.

Mathematical model used in this paper was discussed in our previous works [8-11]. This is system of spatially one-dimensional heat and mass transfer equations with combined kinetic-thermodynamic block for solving problem of chemical transformations. Similar models were used in [7, 11-17] to evaluate characteristics of gasification process.

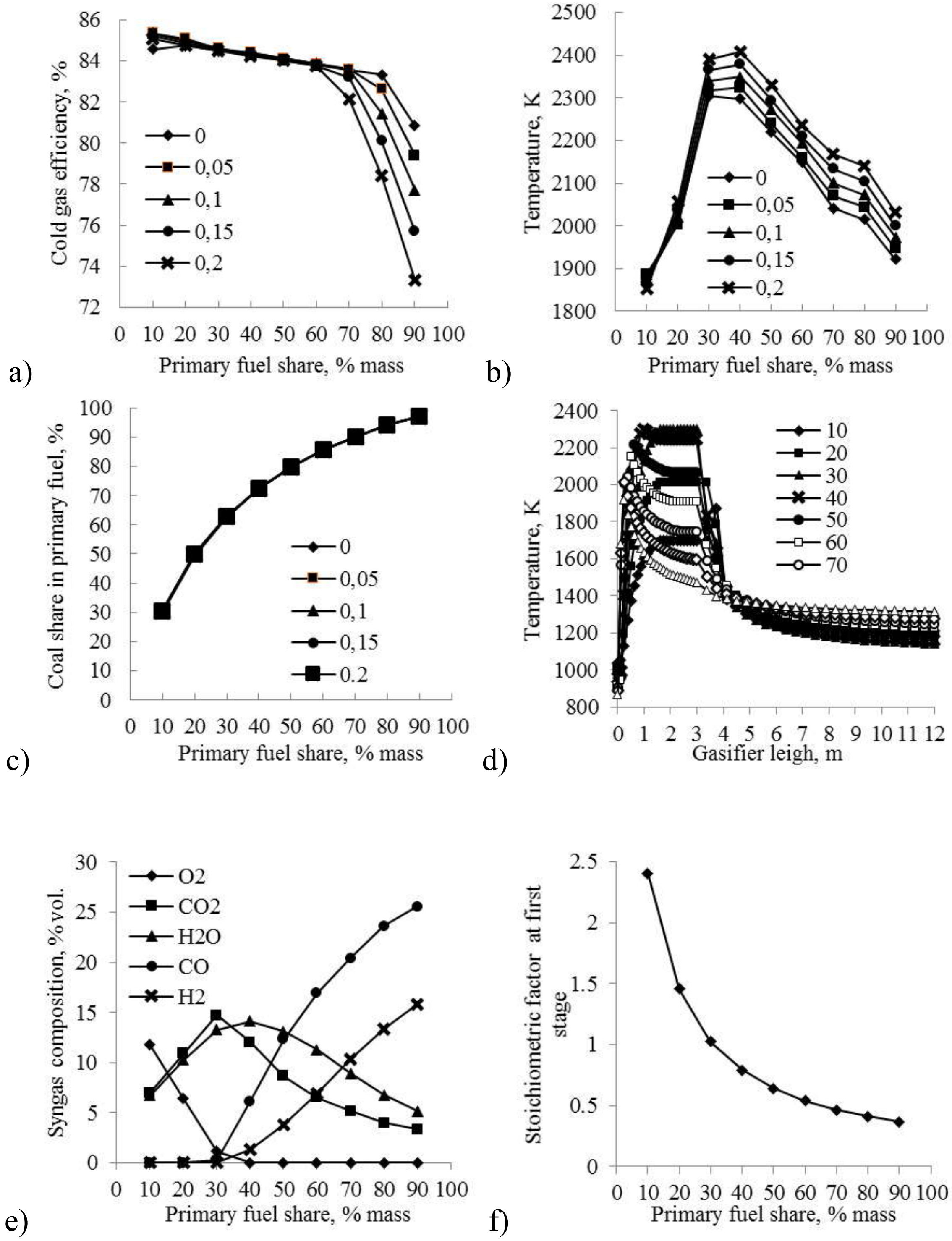
Model is based on thermal balance of carbon particles and the adjacent gas film. Following assumptions about gasification process are accepted: drying rate is limited by external mass exchange with surrounding air; pyrolysis rate is proportional to content of volatiles in particle and depends on temperature according to Arrhenius law; gasification rate is determined from summing of diffusion and kinetic resistances.

Gas-phase chemical kinetics is not considered: gaseous substances are at state of chemical equilibrium. Thus, chemical transformations are described using thermodynamic model with macrokinetic constraints concerned with the rate of heterogeneous transformations. This approach is applicable to high-temperature processes, in which rate of gas-phase processes is quite high in comparison with rate of heterophase processes.

Model contains equations of combined heat transfer (convective and radiant) between fuel particles and gas phase. Wall temperature is considered equal to fuel temperature, i.e. process is considered as adiabatic. This circumstance further simplifies calculations, since it allows to ignore peculiarities of heat exchange with wall and in cooling jacket. In more precise formulation, however, it is necessary to take into account heat transfer with gasifier wall, including thermal resistance of slag films [11].

3.2. Modeling results

In calculations, influence of two parameters is considered: the secondary steam flow (primary steam flow rate is determined by balance), and fuel distribution in steps: from 10%/90% to 90%/10%. As can be seen from Fig. 2a, cold gas efficiency close to equilibrium is reached at primary fuel ratio of 10-40%, its further growth reduces temperature in combustion gasifier (Fig. 2b). Temperature of gas after second stage increases monotonically, reaching value close to equilibrium value (1373 K). Entrainment of hot coking residue increases heat loss of the gasifier. As can be seen from Fig. 2c, fraction of coal in mixture with recycled coke- solic residue can be as low as 30%.



Cold gas efficiency, %
86
84
82
80
78
76
74
72
0
0,05
0,1
0,15
0,2
0 10 20 30 40 50 60 70 80 90 100
Primary fuel share, % mass
a)
Temperature, K
2500
2400
2300
2200
2100
2000
1900
1800
0
0,05
0,1
0,15
0,2
0 10 20 30 40 50 60 70 80 90 100
Primary fuel share, % mass
b)
Coal share in primary fuel, %
100
90
80
70
60
50
40
30
20
10
0
0
0,05
0,1
0,15
0.2
0 10 20 30 40 50 60 70 80 90 100
Primary fuel share, % mass
c)
Temperature, K
2400
2200
2000
1800
1600
1400
1200
1000
800
10
20
30
40
50
60
70
0 1 2 3 4 5 6 7 8 9 10 11 12
Gasifier leigh, m
d)
Syngas composition, % vol.
30
25
20
15
10
5
0
O2
CO2
H2O
CO
H2
0 10 20 30 40 50 60 70 80 90 100
Primary fuel share, % mass
e)
Stoichiometric factor at first stage
2.5
2
1.5
1
0.5
0
0 10 20 30 40 50 60 70 80 90 100
Primary fuel share, % mass
f)

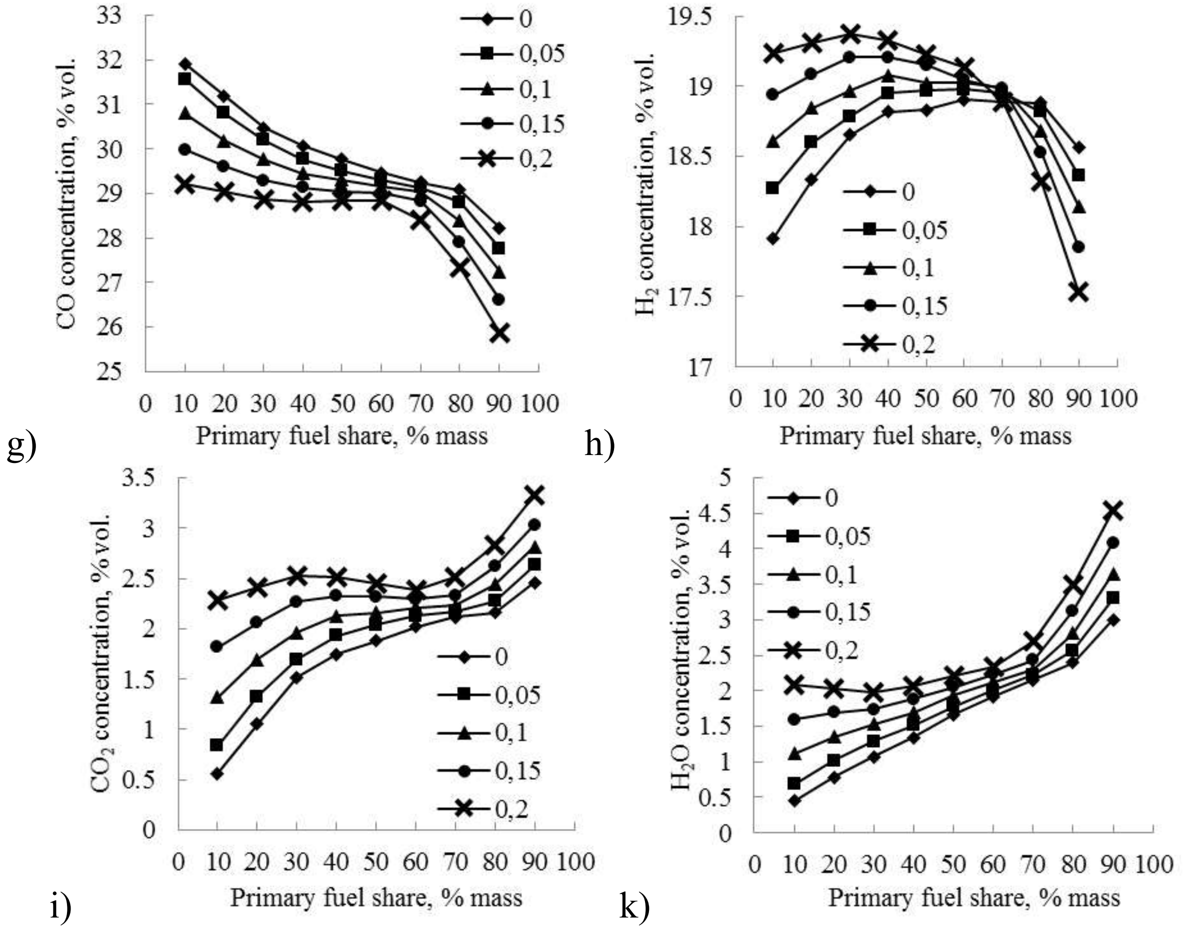


Figure 2. Influence of fuel and steam flow (mol/mol of carbon) distribution of on gasifier operating modes: a) cold gas efficiency; b) maximum temperature at first stage; c) fraction of raw coal in mass flow rate of solid phase entering first stage; d) temperature profile of reaction zone; e) syngas composition; f) oxidizer excess ratio at first stage; g) CO concentration; h) H_2 concentration; i) CO_2 concentration; k) H_2O concentration.

With low portion of primary fuel, its complete combustion occurs, so at 30% the maximum temperature of the first stage is reached. With increase in portion of primary fuel above 30-40%, gasification of carbon with carbon dioxide and water vapor begins already at first stage, so peak temperature decreases. On the other hand, at same time, underfiring of primary fuel increases, which leads to increase of effective stoichiometric factor (this is associated with increase in the temperature of gas leaving gasifier and reduction in the cold gas efficiency with high portion of primary fuel).

Temperature profiles of gasifier are shown in Fig. 2d. Rapid cooling of syngas by heating and drying the secondary fuel leads to sharp change in temperature at around 3 m. Then, heterogeneous chemical reactions begin: with small fraction of primary fuel, presence of residual oxygen leads to development of exothermic reactions. With primary fuel fraction higher than 20-30% molecular oxygen in products of first stage is absent. With high proportion of primary fuel, temperature profiles take form characteristic of single-stage process. Stoichiometric factor of first stage α1 and syngas composition of first stage are shown in Fig. 2e: it is evident that with high portion of primary fuel, main part of combustible gases is provided by first stage. Thus, with primary fuel fraction less than 30-40%, regimes with pronounced two-staged type of temperature profile are realized. Higher portion of primary fuel closer process to usual single-stage gasification process.

Final compositions of syngas are shown in Fig. 2e. For all species, curve varies before and after primary fuel fraction at 60-70%. As already mentioned, with this fraction significant amount of underburning begins at the first stage, which leads to observed pattern. This kink can serve as upper limit of fraction of primary fuel when selecting operating mode of staged gasifier.

4. Three-dimensional modeling

4.1. Model description

In this paper, previously developed computational fluid dynamics (CFD) model for entrained-flow gasification of solid fuels is used [18]. Simulation was carried out on unstructured grid with 550 thousand elements. Grid size was chosen according to following procedure: composition obtained on grids with sizes from 100 to 1000 thousand elements was compared, grid size was considered satisfactory, in which further increase of grid does not affect composition of syngas by more than 3%. Basic equations of CFD modeling include following equations: continuity, energy, components transport, balance of forces for discrete phase, law of momentum conservation, etc. The k-ε turbulence submodel was used, verification of which was given in [18]. Discrete radiation submodel (32 beams) with submodel of gray gases was used as radiation submodel. Heterogeneous reaction submodel is diffusion-kinetic model with kinetic constants obtained by thermogravimetric analysis [19]. Number of fuel particles trajectories was 2000. Adherence condition was satisfied on walls. As calculation algorithm, Fully Coupled Solver is chosen in which velocity and pressure are determined simultaneously.

4.2. Modeling results

Three-dimensional model and two-dimensional projections of modernized gasifier are shown in Fig. 3. Simulation parameters are given in Table 3. Used stoichiometric factor ensured flow of process near thermodynamic equilibrium point taking into account supplied steam. Air is enriched with oxygen up to 25%. Transportation of coal and char is carried out by nitrogen. In second stage, steam is supplied with sufficient flow rate to provide syngas temperature at outlet of gasifier of 1100-1200°C. Blast air and steam have temperature of 900°C. Parameters of gasifier are selected taking into account recommendations obtained as result of above described zero-dimensional and one-dimensional calculations.

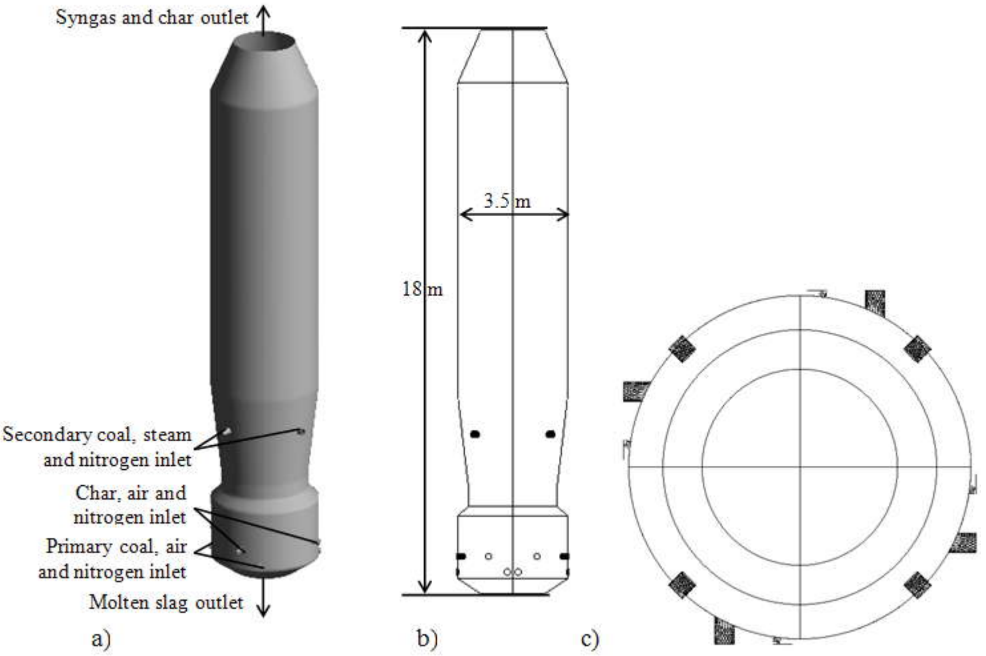


Figure 3. Modernized gasifier: a) 3-D view; b) longitudinal section; c) transverse section.

Table 3. Gasifier inlet flow characteristics

Mass flow rate, kg/s	Primary coal	Char	Secondary coal
Coal	4,03	9,49	15,65
Air	21,57	21,57	0
Nitrogen	0,54	1,28	4,81
Steam	0	0	2,7

Modernized gasifier CFD modeling results are shown in Fig. 4.

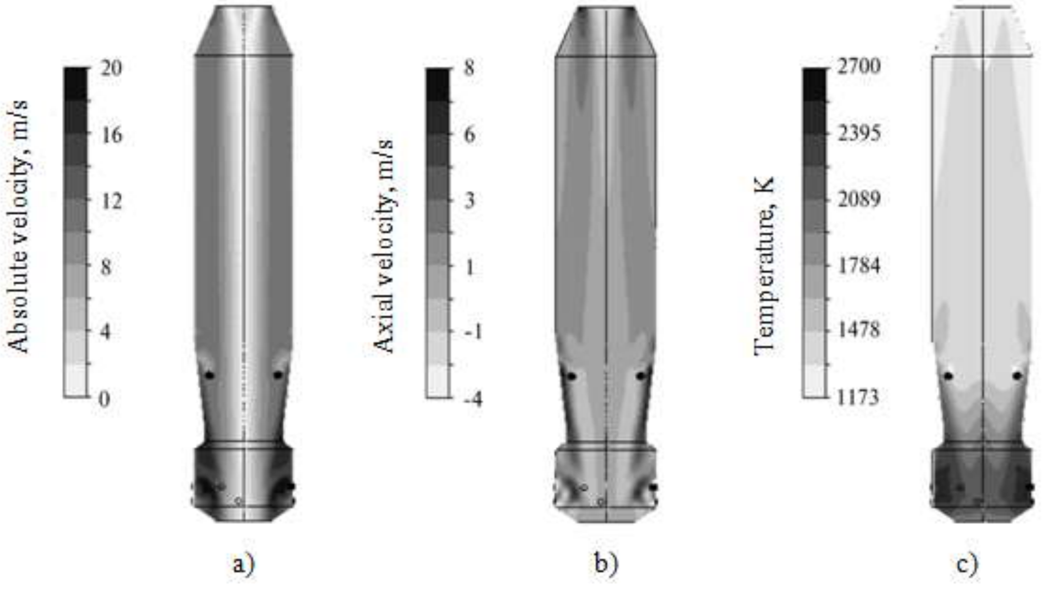


Figure 4. Distribution of: a) absolute velocity, b) axial velocity and c) temperature in longitudinal section of modernized gasifier

Highest absolute velocities (up to 20 m/s) are observed in first stage at outlet from nozzles. Peaks axial velocities (up to 8 m/s) are located along walls of diffuser, but do not extend to second stage. Slag mode depends on flow velocity at pinching point - it should not be large. Reverse currents are most developed in first stage (up to 4 m/s) and weaken in second, which avoids slagging. Temperature reaches highest values (up to 2700 K) in combustion chamber, and in gasification chamber, it decreases due to above-described chemical quenching.

Syngas composition and gasifier characteristics are shown in Table 4.

Table 4. Comparison of MHI and Ural Federal University (UrFU) gasifiers

Gasifier	Dry syngas composition, % vol.					Outlet temperature, K	Heating value, MJ/m^3	Cold gas efficiency, %
	CO	H_2	CO_2	CH_4	N_2			
Commercial MHI [20]	30,5	10,5	2,8	0,7	55,5	1373–1473	5,24	77,2
Modernized UrFU	27,83	16,75	4,78	2,4	46,25	1380	6,56	84,9

Modernization of gasifier MHI type allows increasing syngas heating value, increasing share of hydrogen, reducing CO concentration and increasing gasifier cold gas efficiency. Further direction gasification process improvement is optimization of steam supply point to second stage, as well as organization of media movement in steps due to angles change of media feeding into gasifier.

5. Conclusion

Modernization consisted in additional air blast heating to 900°C by high temperature air heater and steam (900°C) supplying in gasifier second stage. Determination of influence of proposed modernization on gasifier characteristics and optimization of its operating parameters were performed by carrying out multivariate calculations by zero-dimensional, one-dimensional and three-dimensional models.

1) Using zero-dimensional equilibrium thermodynamic model parameters range is investigated in widest intervals. From plurality of "coal-blowing" system, states selected most efficient ones according to criterion of cold gas efficiency with minimum temperature limitations.

2) Achievability of these states was investigated by one-dimensional kinetic-thermodynamic model, which takes into account kinetics of fuel conversion in gasifier. Using this approach it was possible to determine optimal operation gasifier regimes by varying proportion of primary and secondary fuel flows.

3) Parameters (founded by previous models) received as input data to CFD-model, which allowed carry out more refined analysis of problem: flame formation and recirculation zone location in gasifier, choice of fuel, air, steam supply point and flow control ways, etc.

The gasifier modernization has improved syngas thermal capacity and cold gas efficiency from 77.2% to 84.9%, and increases H_2/CO from 0.344 to 0.602. The IGCC efficiency was increased from 48 to 50-52%.

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