바이오매스 가스화를 이용한 열과 전력 결합 플랜트의 에너지 분석

Introduction

There exists a problem of the choice of energy technology from the point of view of the effective utilization of biomass chemical energy, and in terms of its impact on environment [1-12]. An energy effective and environmentally friendly technology may involve the use of biomass for cogeneration of electric energy and heat in gas combined heat and power (CHP) plants integrated with biomass gasification. In CHP plants integrated with biomass gasification there are two new elements as compared with conventional (steam) CHP plants: the application of biomass gasification instead of biomass combustion and the application of gas cycle instead of steam cycle. The technology applied in gas CHP plants integrated with biomass gasification is advantageous from the point of view of energy effectiveness and ecology.

The paper presents the analysis of four technological systems of CHP plants integrated with biomass gasification: :

a) gas CHP plant using simple gas turbine cycle (Fig. 1),

b) two gas CHP plants using steam injected gas turbine (STIG) cycle (Fig. 2 and 3),

c) gas-steam CHP plant (Fig. 4).

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

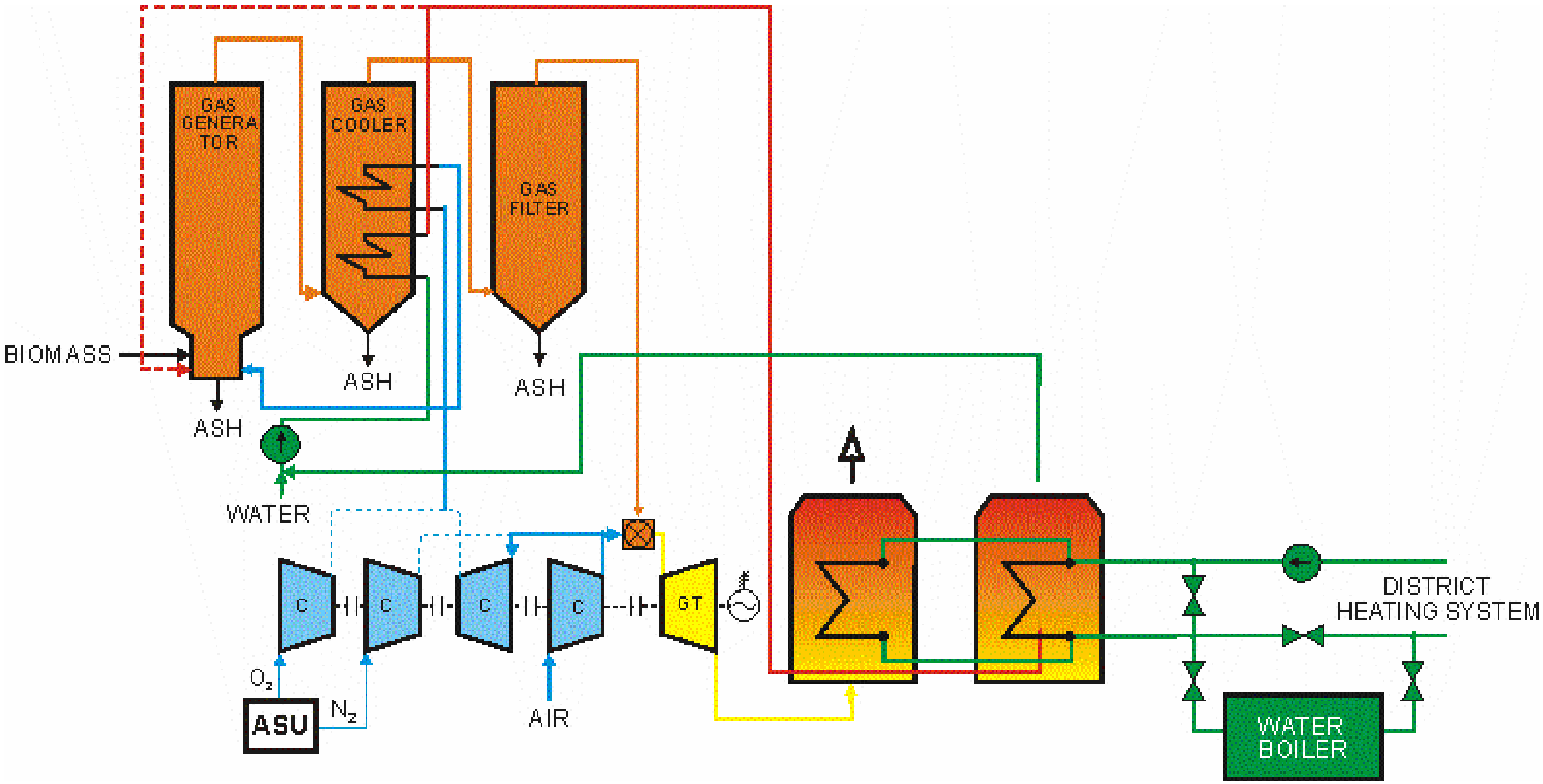

Figure 1. Technological system of gas CHP plant integrated with biomass gasification using simple gas turbine cycle

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

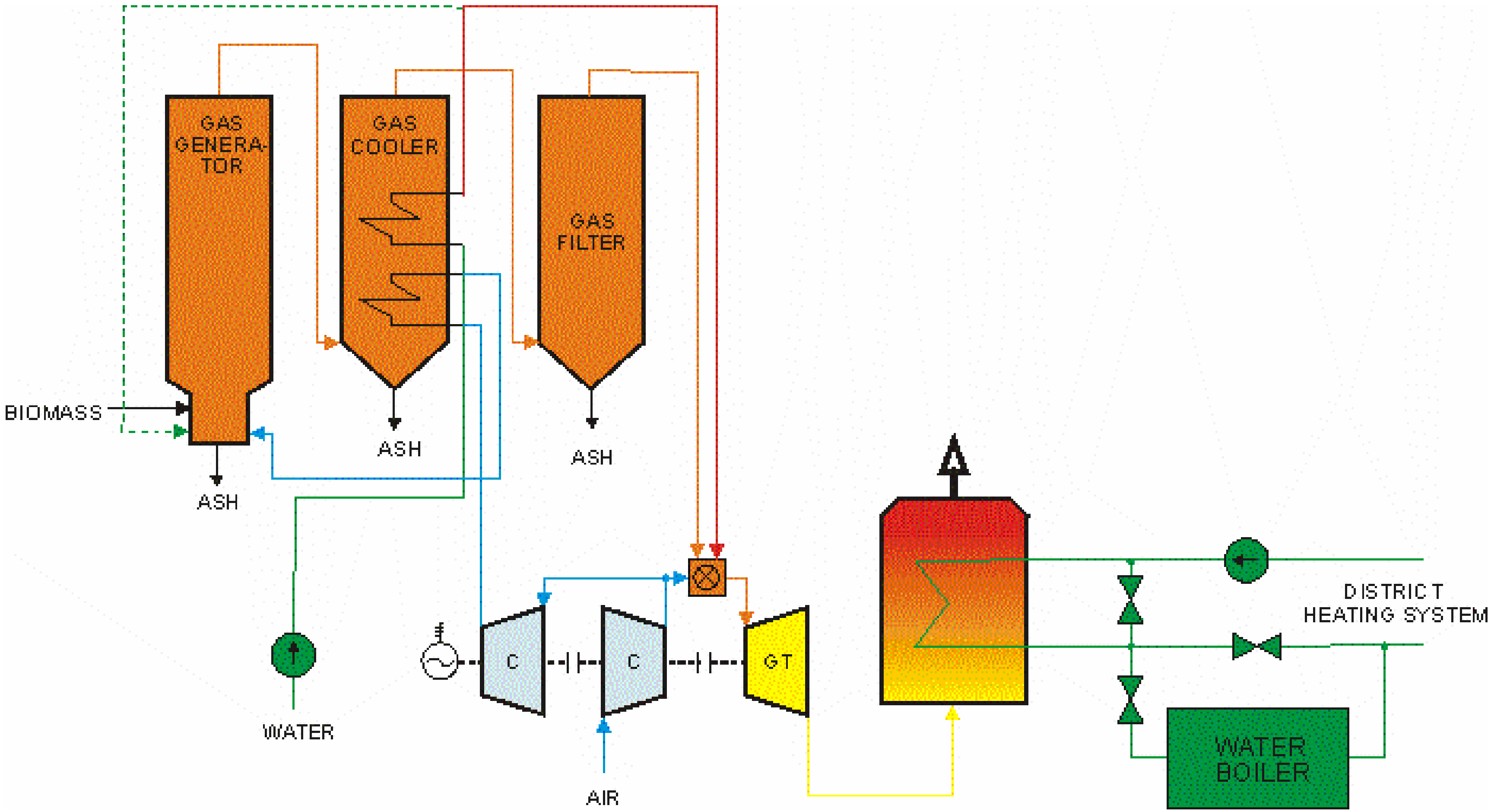

Figure 2. Technological system of gas CHP plant integrated with biomass gasification using steam injected gas turbine (STIG) cycle

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

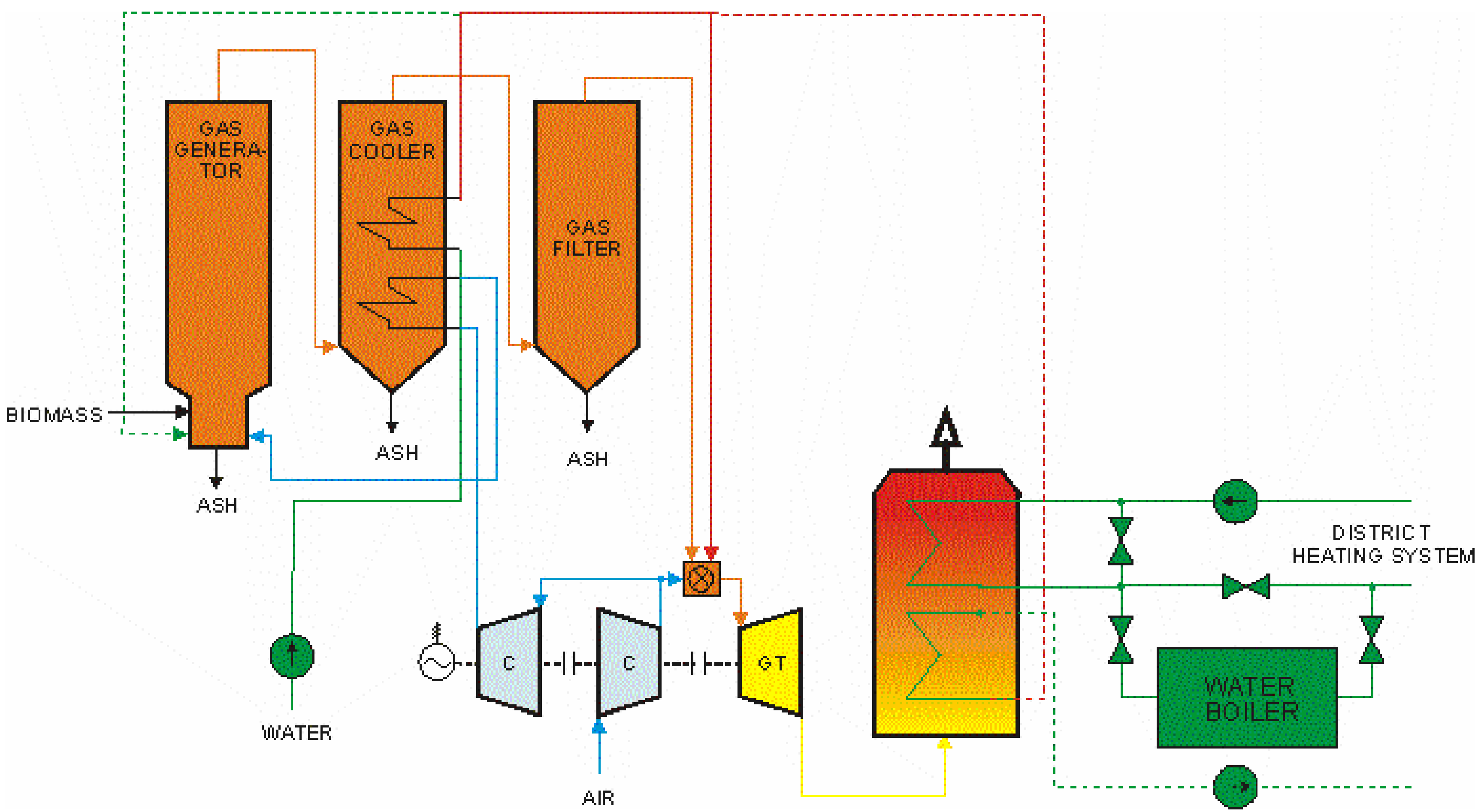

Figure 3. Technological system of gas CHP plant integrated with biomass gasification using steam injected gas turbine (STIG) cycle

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

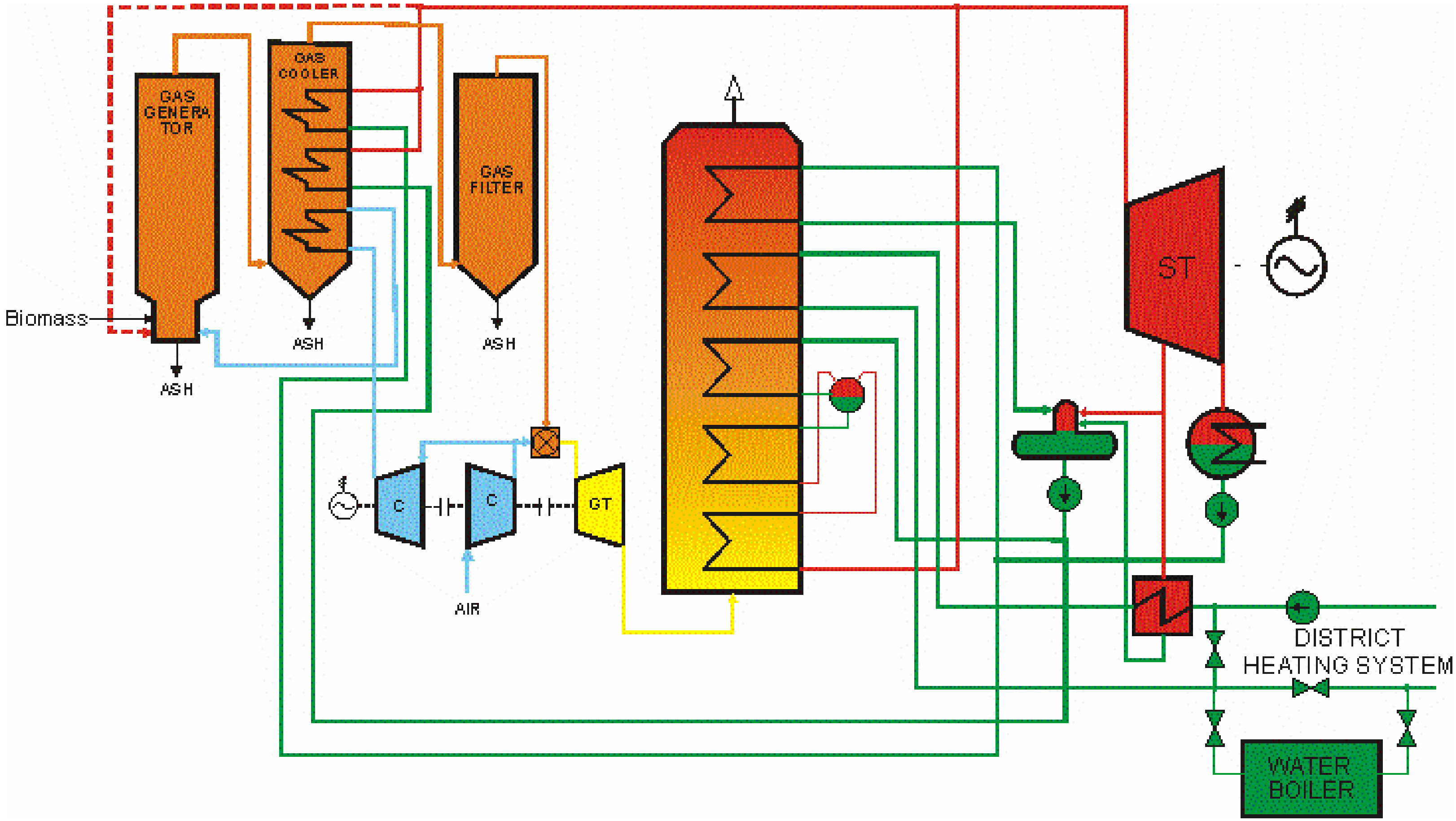

Figure 4. Technological system of gas-steam CHP plant integrated with biomass gasification

In produced gas the following components were present:

CH_4, NH_3, CO_2, H_2O, N_2O, NO_2, SO_2, COS, H_2S, HCN, CS_2, CO, CN, OH, NO, CS, SO, C_2, H_2, O_2, N_2, S_2, C, H, O, N, S and Ar,

Mathematical model

- * 22 equations, which describe chemical reactions proceeding in gas generator,
- * 5 equations of the balance of elements,
- * 1 equation of the balance of partial pressures of the components of gas.

- * equation of the balance of energy of gas generator

$$\frac{1}{\sum_{i=1}^{i=28} M_i p_{gi}} \sum_{i=1}^{i=28} p_{gi}\left(\Delta H_{i(T_0,T_g)} + \Delta H_{gi(T_0)}\right) - a\Delta h_{b(T_0)} - b\frac{1}{\sum_{i=1}^{i=n} M_i p_{gmi}} \sum_{i=1}^{i=n} p_{gmi}\Delta H_{i(T_o,T_{gm})} -$$

$$- c\left(\Delta h_{H_2O(T_0,T_{H_2O})} + \Delta h_{H_2O(T_0)}\right) + d\Delta h_{A(T_0,T_g)} + \Delta Q = 0$$

Chemical efficiency of biomass gasification process :

$$\eta_{ch} = \frac{v_g Q_h^g}{Q_h^b}$$

Energy efficiency of biomass gasification process :

$$\eta_T = \frac{v_g \left(Q_c^g + \frac{1}{22{,}4136} \Delta H_{(T_0, T_g)} \right) - v_{gm} \frac{1}{22{,}4136} \Delta H_{(T_0, T_{gm})} - q_{H_2O} \Delta h_{(T_0, T_{H_2O})}}{Q_h^b}$$

The changeable parameters in particular variant of simulation were:

- temperature of gasification process,
- kind of gasifying agent,
- temperature of gasifying agent.

In each variant of biomass gasification there were calculated:

- composition of gas,
- volume of gas obtained from 1 kg of biomass,
- gasifying agent excess ratio,
- gasifying agent consumption per 1 kg of biomass,
- lower heating value of gas,
- chemical efficiency of gasification process,
- energy efficiency of gasification process.

Composition of biomass assumed in calculations:

C=46.5%	**H=5.70%**	**S=0.03%**
O=40.2%	**N=0.19%**	**W=6.0%**
A=0.38%		

Simulation of biomass gasification

The results of simulation of biomass gasification process (1)

Number of biomass gasification technology	1	2	3	4	5	6
Gasification pressure [MPa]	1.8	1.8	1.8	1.8	1.8	1.8
Gasification temperature [K]	1100	1100	1100	1100	1200	1000
Gasifying agent	air	air+ H_2O	oxygen	air heated to 1000 K	air	air
Gasifying agent excess ratio	0.3300	0.3417	0.2678	0.2923	0.3805	0.2286
Gasifying agent temperature [K]	695	695	695	1000	695	695
Gasifying agent consumption per 1 kg of biomass [Nm^3/kg]	1.4441	1.4953	0.2455	1.2791	1.6651	1.004
Steam consumption per 1 kg of biomass [kg/kg]	-	0.3	-	-	-	-
Volume of gas obtained from 1 kg of biomass [Nm^3/kg]	2.6328	3.0839	1.3751	2.4726	2.8920	2.0053

Simulation of biomass gasification

The results of simulation of biomass gasification process (2)

Number of biomass gasification technology		1	2	3	4	5	6
Main components of produced gas [%]	CO	22.73	16.16	40.51	24.71	22.34	21.47
	H2	16.56	19.08	25.62	17.46	16.11	11.65
	CH4	1.80	0.94	7.79	2.53	0.17	9.29
	CO2	8.83	11.38	15.57	8.28	7.86	13.04
	H2O	6.77	14.15	10.37	6.16	8.07	5.13
	N2	42.76	37.80	0.11	40.34	44.88	38.92
	Ar	0.54	0.47	0.00	0.51	0.56	0.49
	COS	0.0069	0.0054	0.0134	0.0073	0.0063	0.0093
	H2S	0.0011	0.0014	0.0019	0.0011	0.001	0.0011

The results of simulation of biomass gasification process (3)

Number of biomass gasification technology	1	2	3	4	5	6
Lower heating value of gaseous fuel [MJ/Nm3]	5.303	4.438	10.673	5.913	4.625	7.298
Chemical efficiency of biomass gasification [%]	84.06	82.39	88.35	88.01	80.47	88.10
Energy efficiency of biomass gasification [%]	98.25	98.25	98.25	98.25	98.25	98.26

Energy analysis of technological systems of CHP plants

For evaluation of energy effectiveness of analyzed technological systems of gas CHP plant integrated with biomass gasification were determined:

- **electric power of gas turbine generator,**
- **thermal power produced in cogeneration,**

and

- **efficiency of electric energy production,**
- **efficiency of heat production in cogeneration,**
- **energy efficiency (energy utilization factor),**
- **cogeneration index (power to heat ratio).**

Efficiency of electric energy generation in gas CHP plant:

$$\eta_{el} = \frac{P_{elgt} - \Delta P_{OX} - \Delta P_{O2}}{B * Q_h^b}$$

Efficiency of electric energy generation in gas-steam CHP plant:

$$\eta_{el} = \frac{P_{elgt} + P_{elst} - \Delta P_{OX} - \Delta P_{O2}}{B * Q_h^b}$$

Energy efficiency of gas CHP plant:

$$\eta_e = \frac{P_{elgt} + Q_c - \Delta P_{OX} - \Delta P_{O2}}{B * Q_h^b}$$

Energy efficiency of gas-steam CHP plant:

$$\eta_e = \frac{P_{elgt} + P_{elst} + Q_c - \Delta P_{OX} - \Delta P_{O2}}{B * Q_h^b}$$

Cogeneration index of gas CHP plant:

$$\sigma_c = \frac{P_{elgt}}{Q_c}$$

Cogeneration index of gas-steam CHP plant:

$$\sigma_c = \frac{P_{elgt} + P_{elst}}{Q_c}$$

Energy balance of combustion chamber of gas turbine, related to 1 kg of combustion gases:

$$\frac{1}{\sum_{i=1}^{i=6} M_i p_{cgi}} \sum_{i=1}^{i=6} p_{cgi} \Delta H_i\left(T_O, T_{cg}\right) - e \frac{1}{\sum_{i=1}^{i=28} M_i p_{gi}} \sum_{i=1}^{i=28} p_{gi}\left(Q_{gi} + \Delta H_i\left(T_O, T_g\right)\right) -$$

$$- f \frac{1}{\sum_{i=1}^{i=3} M_i p_{oxi}} \sum_{i=1}^{i=3} p_{oxi} \Delta H_i\left(T_O, T_{ox}\right) - g \Delta h\left(T_O, T_{N_2}\right) + h \Delta h\left(T_O, T_{H_2O}\right) + \Delta Q = 0$$

Gaseous fuel produced in the process of biomass gasification before cleaning is cooled to the temperature required by this process.

Two technologies of gaseous fuel cleaning were considered:

- **cold gas cleanup (383K),**
- **hot gas cleanup (811K).**

All the variants of simulation calculations were performed for the same gas turbine with the following parameters:

- **inlet gas temperature $T_{cg1} = 1333$ K,**
- **outlet gas temperature $T_{cg2} = 763$ K,**
- **pressure ratio $\Pi = 16.0$**

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

The results of energy calculations of technological systems of gas and gas-steam CHP plant integrated with biomass gasification for **cold** gas cleaning method (part 1)

Parameter	Variant (figure) number								
	1	1	1	1	1	1	2	3	4
Number of biomass gasification technology	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**1**	**1**
Inlet gas temperature of gas turbine [K]	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**
Outlet gas temperature of gas turbine[K]	**763**	**763**	**763**	**763**	**763**	**763**	**763**	**763**	**763**
Biomass consumption [kg/s]	**1.582**	**1.677**	**1.389**	**1.496**	**1.677**	**1.483**	**1.636**	**1.687**	**1.597**
Electric power of gas turbine generator [MW]	**7.81**	**8.43**	**7.64**	**7.74**	**7.90**	**7.72**	**9.24**	**10.60**	**7.82**
Electric power of steam turbine generator [MW]	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**2.72**

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

The results of energy calculations of technological systems of gas and gas-steam CHP plant integrated with biomass gasification for **cold** gas cleaning method (part 2)

Parameter	Variant (figure) number								
	1	**1**	**1**	**1**	**1**	**1**	**2**	**3**	**4**
Number of biomass gasification technology	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**1**	**1**
Thermal power produced in cogeneration [MW]	**15.50**	**16.89**	**13.23**	**14.16**	**16.94**	**13.95**	**11.55**	**7.61**	**11.62**
Energy efficiency (energy utilization factor)[%]	**88.34**	**84.18**	**88.53**	**87.78**	**88.74**	**87.73**	**7608**	**64.63**	**83.24**
Efficiency of electric energy generation [%]	**29.35**	**29.88**	**31.19**	**30.80**	**27.93**	**31.08**	**33.61**	**37.46**	**39.40**
Cogeneration index (power to heat ratio)	**0.504**	**0.499**	**0.577**	**.547**	**0.466**	**0.553**	**0.800**	**1.393**	**0.907**
Content of H_2O in combustion gases [%]	**5.412**	**8.68**	**4.77**	**5.12**	**5.74**	**5.08**	**13.08**	**20.00**	**5.41**

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

The results of energy calculations of technological systems of gas and gas-steam CHP plant integrated with biomass gasification for **hot** gas cleaning method (part 1)

Parameter	Variant (figure) number								
	1	1	1	1	1	1	2	3	4
Number of biomass gasification technology	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**1**	**1**
Inlet gas temperature of gas turbine [K]	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**	**1333**
Outlet gas temperature of gas turbine[K]	**763**	**763**	**763**	**763**	**763**	**763**	**763**	**763**	**763**
Biomass consumption [kg/s]	**1.399**	**1.437**	**1.306**	**1.339**	**1.455**	**1.345**	**1.416**	**1.491**	**.405**
Electric power of gas turbine generator [MW]	**7.65**	**8.14**	**7.57**	**7.59**	**7.70**	**7.60**	**8.17**	**10.55**	**7.65**
Electric power of steam turbine generator [MW]	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**2.10**

Simulation of energy effectiveness of CHP plants integrated with biomass gasification

The results of energy calculations of technological systems of gas and gas-steam CHP plant integrated with biomass gasification for **hot** gas cleaning method (part 2)

Parameter	Variant (figure) number								
	1	1	1	1	1	1	2	3	4
Number of biomass gasification technology	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**1**	**1**
Thermal power produced in cogeneration [MW]	**12.68**	**13.22**	**11.88**	**11.75**	**13.55**	**11.87**	**11.19**	**4.26**	**9.63**
Energy efficiency (energy utilization factor)[%]	**87.08**	**82.71**	**87.74**	**86.67**	**87.49**	**86.91**	**81.03**	**59.44**	**82.72**
Efficiency of electric energy generation [%]	**32.54**	**33.69**	**32.96**	**33.82**	**31.42**	**33.76**	**34.35**	**42.24**	**42.44**
Cogeneration index (power to heat ratio)	**0.603**	**0.616**	**1.839**	**0.646**	**0.568**	**0.640**	**0.730**	**2.477**	**1.012**
Content of H_2O in combustion gases [%]	**4.79**	**7.44**	**4.48**	**4.58**	**4.98**	**4.60**	**7.64**	**20.00**	**4.79**

Conclusions

The results of simulations allow one to formulate the following conclusions:

- **The kind of gasifying agent has a significant impact on the chemical efficiency of the biomass gasification process and on the lower heating value of the produced gas. Water steam added to gas generator decreases the energy efficiency.**
- **The kind of gaseous fuel cleaning technology has a significant impact on the efficiency of electric energy generation. The replacement of the cold gas cleaning method with the hot gas cleaning method allows the efficiency of electric energy generation to increase by around 3% in simple gas turbine cycle, and by around 5% in STIG cycle.**

Conclusions

- **Interesting simulation results were obtained for the technological system using steam injection to combustion chamber of gas turbine (STIG cycle). When the content of water steam in combustion gases is 20% (in this cycle), the efficiency of electric energy generation increases to 37.46%, for cold gas cleaning method, and to 42.24%, for hot gas cleaning method. However the energy efficiency of CHP plant decreases respectively to 64.63% and to 59.44% (Table 2).**

Conclusions

- **Among the investigated technological systems of CHP plants integrated with biomass gasification, the highest electric energy generation efficiency and a high energy efficiency is being obtained in technological systems of gas steam CHP plants (Figure 4). However, on the small scale this system has the highest investment cost.**