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Integration of a selected district heating system with an installation for cogasification of coal and biomass

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Abstract. The article presents a topic related to generation of heat and power in small and medium size coal power units which are able to comply with the emission benchmark of 550 g of CO_2/kWh through utilization of biomass. The concept for coal and biomass cogasification installation is based on GazEla reactor, which has been developed by Institute for Chemical Processing of Coal. Authors also present a discussion on issues related to technological scheme of the gasification unit which has been integrated with a selected district heating system. The system has been set up for generation of hot technological water and electrical power. Focal point of the installation is a fixed bed gasification reactor. For the system to provide means enabling cogeneration of heat and power, downstream from the generator a high-temperature gas dedusting system, a unit for recovery of heat from process gas coupled with separation of tar contaminants as well as a gas engine were proposed. A sorted chart presenting historical data for annual demand for heat together with the most important assumptions used during the analyses are discussed. Finally authors present results of calculations for the integrated unit that are further broadened by sensitivity analyses for change of gasification reactor's efficiency, as well as engine's efficiency for heat and power generation.

1. Introduction

In recent days there is a clear trend for shift in legal and formal regulations regarding energy sector to impose the need for search of new and innovative solutions that will allow for generation of heat and power with higher efficiencies, lower environmental emissions as well as will utilize higher amounts of renewable energy source (RES), i.a of biomass [1, 2].

The subject is particularly important for currently operating small and medium size of power generating systems which operate on traditional primary fuels, eg. coal barley, which face today the challenge of adaptation to new regulations, eg. environmental ones. Another important aspect of the problem is also connected with emission of CO_2, which mainly pertain to the planned UE directive which will impose the criteria for CO_2 emission below the level of 550 g/kWh. Power stations with higher emissions of CO_2 will be obligated to pay additional money for their emissions within the frame of ETS scheme. This on the other hand will influence highly the final cost of energy production. This is particularly importation in the light of recent rise in the prices of CO_2 emission equivalent cost, which at the beginning of 2019 reached the level of 23.7 €/t, and which according to long term forecasts will stay on a rise for many years to come [3, 4].

One of the solutions discussed frequently for small and medium scale units, which allows for an efficient utilization of heat and power, both regarding environmental and energetic considerations is gasification technology [5, 6]. This technology enables generation of heat and power in cogeneration units based on piston engines. The solid fuels through gasification are converted into syngas which after upgrading and cleaning has excellent properties as a gaseous fuel. Combustion of such gas in piston engines provides energy for operation of electricity generators and produces high temperature flue gases, which through cooling and heat recovery allow for generation of useful heat. This heat can be than connected with another source of high temperature heat, which in gasification installations is found from cooling of the process gas [6, 7].

The article presents topics related to integration of a gasification installation with a selected local heating grid, which allows for exchange of coal fired water boiler operated for production of hot water during the entire year, as well as utilization of the generated power when considering the 550 g/kWh criteria, through utilization of coal and biomass cogasification technology.

2. Gasification technology – GazEla reactor

The technology for gasification of solid fuels is based on reactors, which depending of efficiency as well as the final means of process gas utilization can be divided into fixed bed reactors, fluidised bed reactors and entrained bed reactors. Process gas, generated within them, may be utilized for direct combustion and generation of high temperature flue gases, feeding of cogeneration units based on piston engines or gas turbines, as well as production of synthetic gases (eg. CH_4 and H_2) or liquid fuels and chemical substances such as methanol or DME.

Institute for Chemical Processing of Coal for many years develops gasification technologies for i.a coals, biomasses and wastes. The research and development works are carried out mainly for energetic utilization of process gases in cogeneration units as well as for production of synthetic gaseous and liquid fuels.

For sake of the analyses presented hereinafter, one of the technologies developed by IChPW has been chosen. The gasification process considered in this article is carried out in fixed bed GazEla reactor. The reactor was designed and developed for the in view of generation of process gas from solid fuels i.e. mainly biomass, for cogeneration of heat and power in gas piston engines. This technology is dedicated for small and medium scale energy systems eg. district heating stations as well as heat and power stations, companies that have technological lines operated on hot water or technological steam as well as companies with large internal demand for electricity.

The gasification installation consists of four main technological blocks, ie. fuel preparation and feeding, GazEla fixed bed gasification reactor, gas cleaning unit and cogeneration unit based on gas piston engine.

Central point of the system is the GazEla reactor, which is a vertical, cylindrical reactor operated under fixed bed conditions. In the vertical axis of the reactor a central pipe is fitted which allows for recovery of process gas directly from gasification zone. Fuel is fed into the reactor from top, while gasification agent is fed into three zones: under reactor's grate, into its middle part as well as above the level of fuel bed. Proper selection of type and stream of gasifying agent is crucial for regulation of load of each process zones of the reactor. This mechanism provides means for control of temperature profiles observed within the reactor and obtaining right process conditions in relation to physicochemical parameters of gasified feedstock [8, 9, 10]. Figure 1 presents a technological scheme of the reactor with denoted specific process zones.

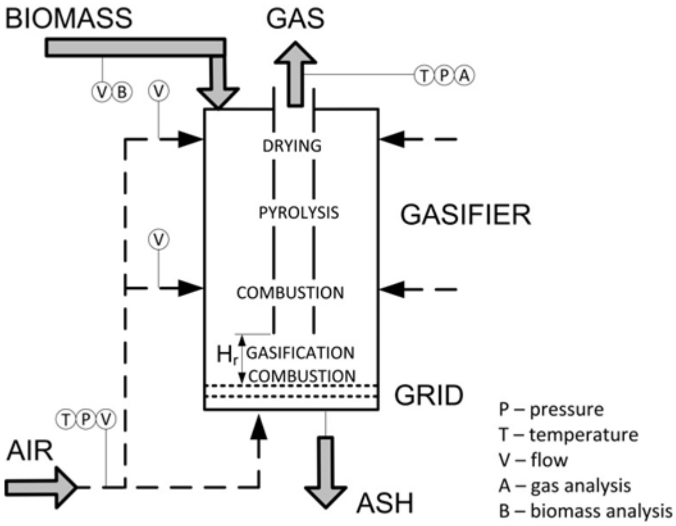

Fig. 1. Technological scheme of GazEla reactor with denoted specific process zones.

In Figure 2 pictures of a pilot GazEla reactor, which is located in Clean Coal Technology Centre of IChPW are presented.

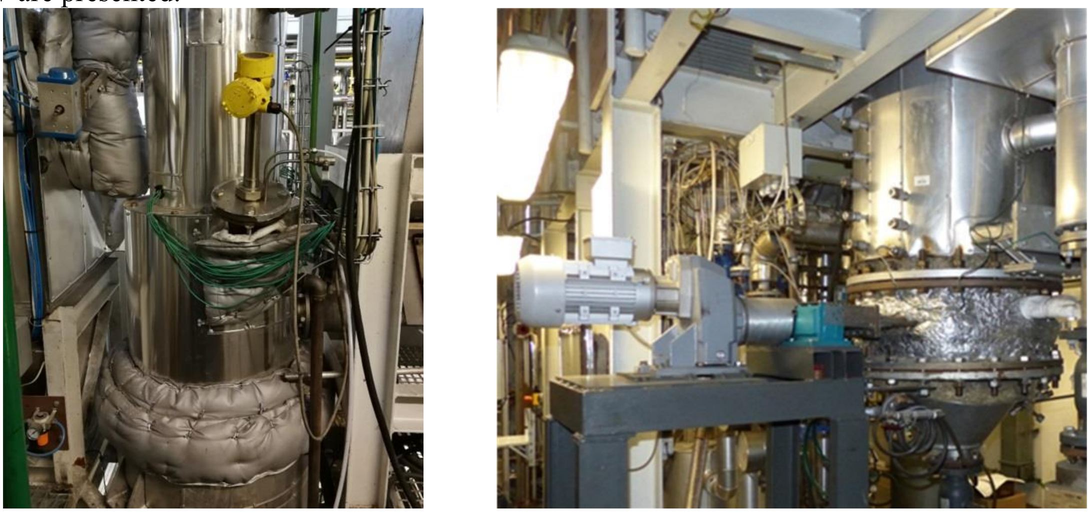

Fig. 2. Pictures of pilot GazEla fixed bed reactor (top and bottom part of the reactor)

3. A reference unit of a coal and biomass cogasification installation integrated with a selected district heating system

As a reference point for the analysis, a heating system located in Miejski Zakład Energetyki Cieplnej w Świdnicy Sp. z o.o. has been taken [11].

Analysis has been done in order to assess the possibility to exchange one of the boilers for a coal and biomass cogasification installation, which allows for yearlong generation of hot water according to current production of the boiler as well as production of electricity while exercising the 550g CO_2/kWh rule.

Figure 3 presented below, represents a sorted chart for annual demand for heat for the selected boiler in year 2018. A minimal daily average outside temperature (atmosphere) was equal to $T_{z\ min}$= -12.0°C, whilst a maximal daily average outside temperatures was equal to $T_{z\ max}$= 29.0°.

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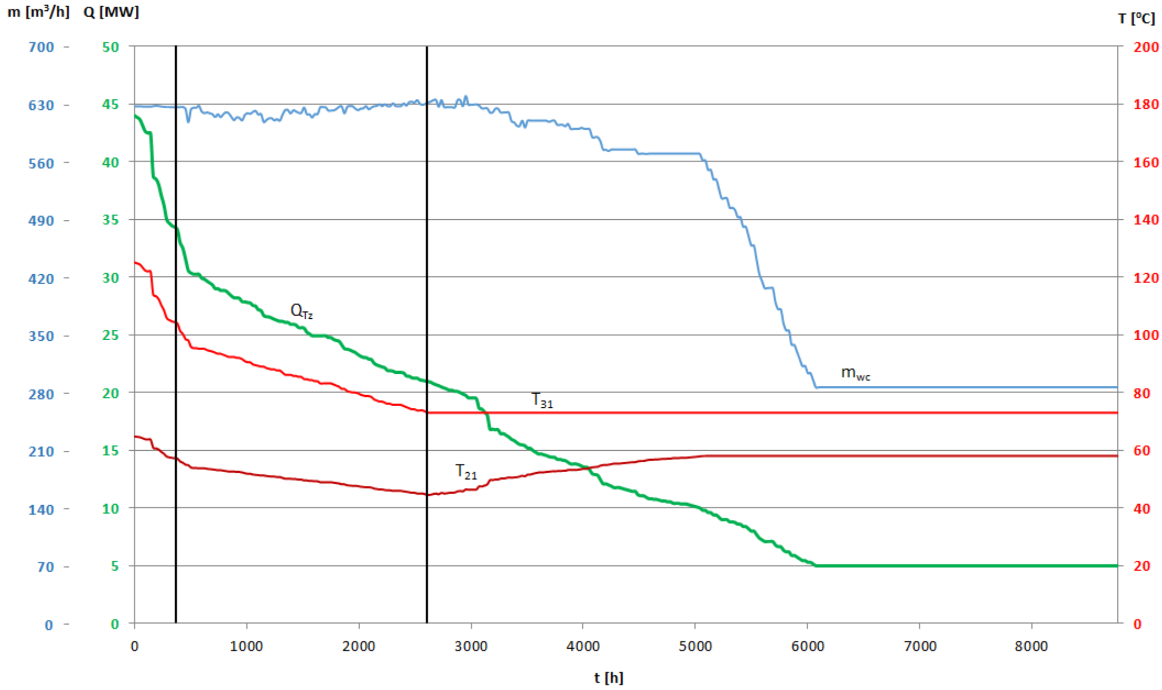

Fig. 3. Sorted annual heat demand chart for the selected water boiler.

Year average daily outside temperatures was equal to $T_{z\ avg}$= 11.2°C. Accordingly, heat demand of the boiler was equal to $Q_{Tz\ min}$= 44.0 MW and $Q_{Tz\ max}$= 5.0 MW. Parameters of the heating water at inlet and outlet from the boiler for $T_{z\ min}$ and $T_{z\ max}$ are presented in Table 1. Line T_{21} represents temperature of inlet (incoming) hot water, whilst line T_{31} depicts temperature of outlet (heated) water. Line m_{wc} describes stream of heating water.

Table 1. Characteristic parameters for selected district heating system.

Parameter	Unit	Value
Minimal power of the heating station, Q_{Tzmax}	MW	5
Maximal power of the heating station, Q_{Tzmin}	MW	44
lowest daily-average outside temp., $T_{z\ min}$	°C	-12
highest daily-average outside temp., $T_{z\ max}$	°C	29
minimal temperature of inlet water, T_{21min}	°C	45
maximal temperature of inlet water, T_{21max}	°C	65
minimal temperature of outlet water, T_{31min}	°C	73
maximal temperature of outlet water, T_{31max}	°C	125
minimal stream of water, m_{wcmin}	m^3/h	286.4
maximal stream of water, m_{wcmax}	m^3/h	639.5

A model based on the concept for gasification unit used for energy and heat production in piston engine has been taken for analysis. Figure 4 shows a block diagram of biomass and coal gasification unit integrated with the selected district heating unit (from Fig. 3).

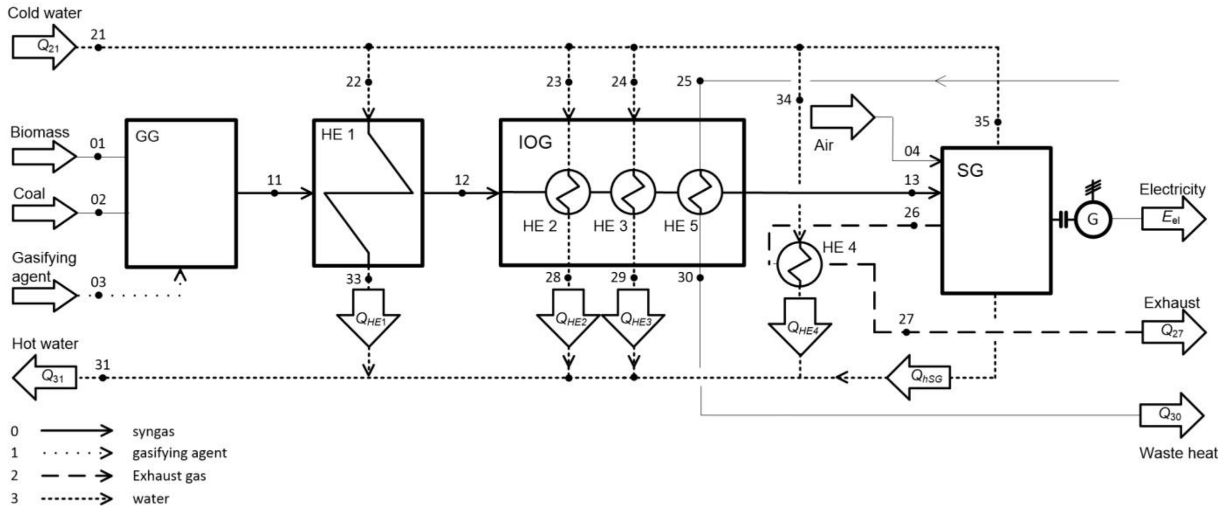

Fig. 4. Block diagram of biomass and coal gasification installation for heat and power production for demand of a district heating unit.

The system presented on Fig. 4 comprises of a gas generator (GG), integrated with a dedusting unit – adiabatic process, as well as gas cooling unit ((HE 1). Next element of the installation is a gas cleaning block (IOG) which separates tar contaminants and is based on three heat exchangers (HE 2, HE 3, HE 5). Cleaned and cooled process gas is directed into piston engine (SG), where heat Q_{hSG} and power E_{el} are cogenerated. Additionally fuel gases are further cooled in heat exchanged (HE 4), where heat Q_{HE4} is generated. Heat streams Q_{HE1}, Q_{HE2}, Q_{HE3} obtained through process gas cooling, afterwards are connected with heat streams generated in piston engine Q_{hSG} and Q_{HE4} and finally together comprise the total usable heat, necessary for heating purposes. In heat exchanger HE 5 the final lowering of process gas temperature to 40°C is done according to technical demands of piston engines. Due to low temperature of water obtained in HE 5, the heat stream Q_{30} is not used for heating of usable hot water and thus is treated as waste.

Table 2 presented bellow shows physicochemical properties of coal and biomass used in the analysis.

Table 2. Physicochemical properties of coal and biomass

Denotation	**Unit**	**Coal**	**Biomass**
Moisture content	%	19.1	22.1
Ash content	%	11.8	1.0
Volatile matter content	%	25.5	63.7
Carbon content	%	56.2	40.3
Hydrogen content	%	3.1	4.5
Nitrogen content	%	0.8	0.1
Oxygen content	%	8.0	32.0
Sulfur content	%	1.0	0.0
Lower heating value	J/g	20 693	14 279

Due to the low power of the installation, it has been assumed that for gasification a fixed bed reactor will be used, which for gasification of biomass is characterized by cold gas efficiency equal to ca. 63.0%. The efficiency is defined by the following equation:

$$\eta_{GG} = \frac{(\dot{m} \cdot LHV)_{11}}{(\dot{m} \cdot LHV)_{01} + (\dot{m} \cdot LHV)_{02}} \quad (1)$$

Where:
m_{11} – mass stream of process gas,
LHV_{11} – lower heating value of the process gas,
m_{02} – mass stream of coal,
LHV_{02} – lower heating value of coal,
m_{01} – mass stream of biomass,
LHV_{01} – lower heating value of biomass,

For purpose of the analysis it has been assumed that air will be the gasification agent.

In order to assure parameters of the heating water for the selected district heating unit during the whole year, as well as to fulfil the CO_2 emission regulation of 550 g of CO_2/kWh, it is necessary to feed the reactor with stream of fuel equal to 2 313.6 kg/h. Mass fractions of biomass and coal in the blend are equal to 71.7% of biomass and 28.3% of coal. Stream of air directed to the gasifier is equal to 3559.9 kg/h. Assumed heating value of the process gas (dry) equals to 4.91 MJ/Nm^3.

Hot process gas recovered from the reactor has 750°C and is cooled in heat exchangers. Stream of heat obtained from gas in the exchangers has been determined with use of the following formula:

$$\dot{Q}_{HEi} = \dot{m}_{gas} \cdot \eta_{HEi} \int_{T_{outi}}^{T_{ini}} c_p(T)dT \quad (2)$$

Where:
Q_{HEi} – stream of heat recovered in heat exchanger,
T_{ini} – gas temperature at the inlet,
T_{outi} – gas temperature at the outlet,
$c_p(T)$ – specific heat capacity of gas at function of temperature,
It has been assumed that efficiency of HEs is equal to 99%.
Total useful heat of the unit is calculated with use of the following formula:

$$\dot{Q}_{heat} = \dot{Q}_{hSG} + \sum_{i=1}^{4} \dot{Q}_{HEi} \; [kW] \quad (3)$$

Another assumption is that HE 1 cools process gas from 750°C to 500°C. This gas is further directed to dedusting. Afterwards, in HE 2 gas is further cooled to temperature 110°C. In HE 3 and HE 5 the gas is cooled to 40°C. Here condensation of water vapour takes place. After the final step of cooling, the gas is directed to combustion in piston engine. Flue gases from the engine are cooled in HE 4 to temperature of 130°C.

For calculations it was set that technological water is the heating medium. Parameters of the water were determined based on the annual demand for technological hot water.

Parameters of the water are accordingly, at summer equal to 73/58°C, while at winter 125/65°C. The installation reaches maximal heating power in the intermediate term, when parameters of water drop down to 74/45°C. For the assumed temperature of heating water, it is not possible to cool down the process gas to the level of 40°C in HE 3. For this reason the additional heat exchanger HE 5 has been set and it is cooled by water chilled by a draft fan cooler. It has been assumed that pinch point in the coolers is equal to 5K. Figure 5 presents a sorted chart of annual temperatures of technological water and their relevant power demands for HE 3 and HE 5. For technological water with parameters above 105/57.5°C it was determined that all heat will be recovered in heat exchanger HE 5.

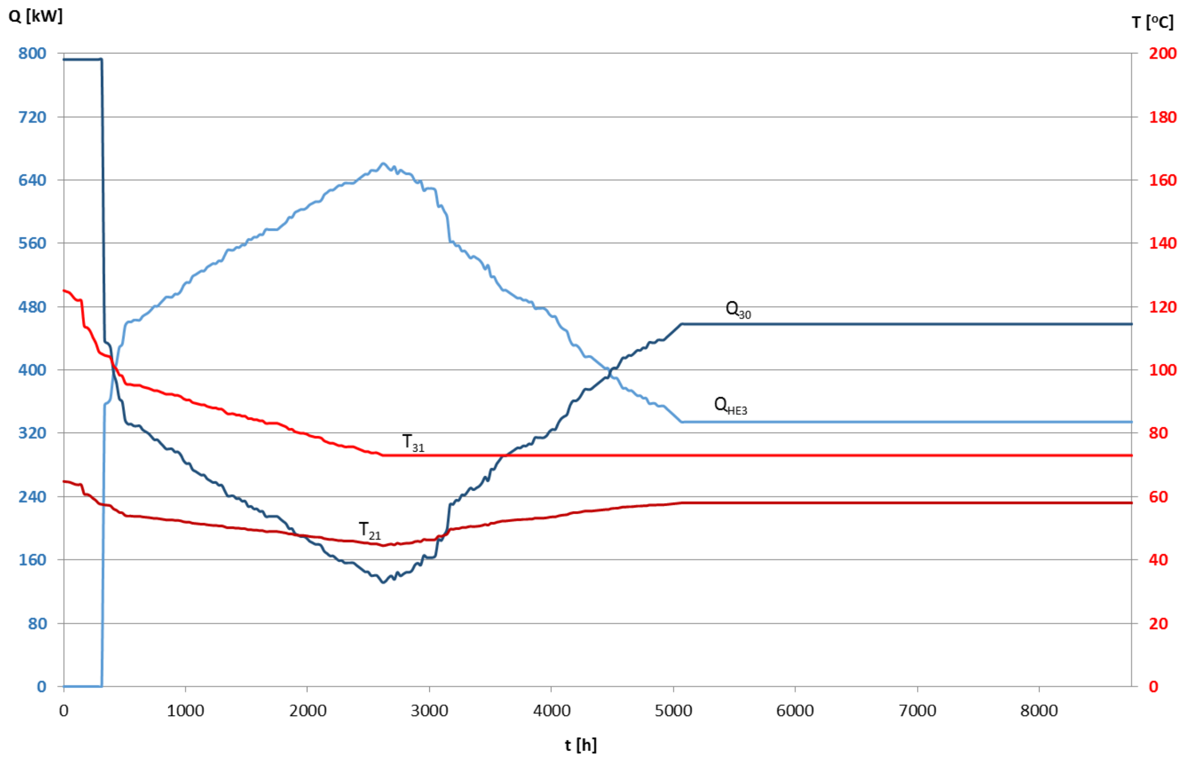

Fig. 5. Sorted chart of annual temperatures of technological water with depicted powers of the heat exchangers HE 3 and HE 5.

A cumulated heat production was calculated by the following formula:

$$Q_{heatref} = Q_{hSG} + \sum_{i=1}^{4} Q_{HEi} \left[\frac{GJ}{year}\right] \quad (4)$$

while heat recovered by each heat exchanger was calculated with:

$$Q_{HEi} = \int_{t_0}^{t_{max}} \dot{Q}_{HEi}(t)dt \left[\frac{GJ}{year}\right] \quad (5)$$

$$Q_{heat} = Q_{heatref} \cdot A \quad (6)$$

where A, is availability of the installation, set as a ratio of the amount of operational hour during a year:

$$A = \frac{t_{work}}{8760} \quad (7)$$

It was assumed that during a year the installation will work 7500 h.

A cumulated heat recovered by the subsequent steps of heat exchangers is presented in table 3.

Table 3. Cumulated heat recovered by heat exchangers

Water temperatures	**°C**	**73/58-73/45**	**73/45-105/57.5**	**> 105/57.5**
Work time	h	6 120	2 328	312
Heat generated				
Heat exchanger 1, Q_{HE1}	GJ	10 379.6	3 948.3	529.2
Heat exchanger 2, Q_{HE2}	GJ	14 898.3	5 667.2	759.5
Heat exchanger 3, Q_{HE3}	GJ	7 430.4	3 954.7	0
Heat exchanger 4, Q_{HE4}	GJ	2 308.8	878.3	117.7
Gas engine, Q_{hSG}	GJ	60 421.1	22 983.7	3 080.3
Waste heat, Q_{30}	GJ	7 514.8	1 730.3	761.9
Net electricity, E_{elnet}	kW	2 195.6	2 200.9	2 182.4

Cooled gas is than burned in piston engine. Efficiency of power generation of the motor is defined by:

$$\eta_{elSG} = \frac{\dot{E}_{elgross}}{(\dot{m} \cdot LHV)_{13}} \quad (8)$$

Heat generation efficiency of the engine was defined as:

$$\eta_{hSG} = \frac{\dot{Q}_{hSG}}{(\dot{m} \cdot LHV)_{13}} \quad (9)$$

It was assumed that efficiency of heat and power generation in a piston engine fuelled by process gas is accordingly equal to η_{hSG} = 49.2% and η_{hSG} = 37.7%. Thus efficiency of cogeneration in the engine is equal to:

$$\eta_{SG} = \frac{\dot{Q}_{hSG} + \dot{E}_{elgross}}{(\dot{m} \cdot LHV)_{13}} \quad (10)$$

The calculations take into account also the power consumed for internal purposes of the unit. It was assumed that the index of internal demand α is equal to 10%. Additionally it was set that power demand to the draft cooler E_{elCT}, is linearly demendant on its capacity which is variable in time. Generated net electrical power was calculated with:

$$\dot{E}_{elnet} = (1 - \alpha)\dot{E}_{elgross} - \dot{E}_{elCT} \quad (11)$$

Total efficiency of cogeneration is determined as a sum of efficiencies of heat and power generation from a fuel:

$$\eta_{CHP} = \frac{\dot{E}_{elnet} + \dot{Q}_{heat}}{(\dot{m} \cdot LHV)_{01} + (\dot{m} \cdot LHV)_{02}} \quad (12)$$

Table 4 presents all the most important assumptions and results of the performed balance calculations.

Table 4. Collation of assumptions and results of calculation

Parameter	Unit	Value
Assumed work time	h/year	7 500
Assumed own need indicator	%	10.0
Fuel mixture stream	kg/h	2 313.6
Gasifier thermal power	kW	10 334.1
Biomass content in fuel	%	71.7
Cold gasification efficiency	%	63.0
Gas engine electricity production efficiency	%	37.7
Gas engine heat production efficiency	%	49.2
Combined heat and power efficiency (for summer parameters)	%	69.63
Calculated total average combined heat and power efficiency	%	70.48
Heat exchangers heating power for water at temperatures 73/58°C	kW	5 000.0
Heat exchangers heating power for water at temperatures 73/45°C	kW	5 318.4
Heat exchangers heating power for water at temperatures 125/65°C	kW	4 665.6
Gross electricity production	kW	2 454.4
Net electricity production for water at temperatures 73/45°C	kW	2 206.9
Net electricity production for water at temperatures 125/65°C	kW	2 182.4
Total demand for chemical energy in fuel	GJ/year	279 070
From coal	GJ/year	101 158
From biomass	GJ/year	177 912
Total heat production	GJ/year	137 357
Total waste heat in draft fan cooler	GJ/year	10 007
Total net electricity produced	MWh	16 473.9

Basing on the abovementioned calculations, a sensitivity analysis has been done for a set of parameters changing based on efficiency of the unit. Fig. 6 presents the impact of change of cold gas efficiency of the gasifier as well as efficiency of power generation and heat generation of the engine, under the assumption that rest of the process parameters remain constant. For nominal efficiency of gasification in the reactor (63.0%) a total efficiency of the installation is equal to 69.63%. For the change of value in range of -3% to +3%, the overall efficiency of the installation changes in the range of 67.13 % ÷ 72.12%. While, for the change in efficiency of power generation of the engine from -3% to +3%, the change of overall efficiency of the installation changes in the range of 67.74% ÷ 71.52%.

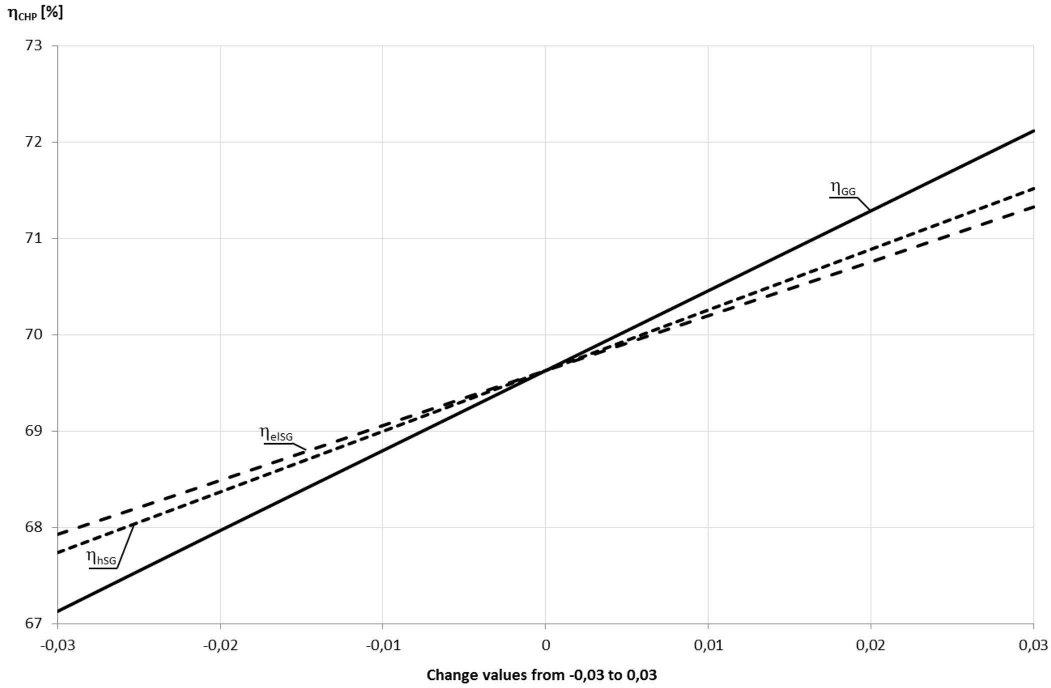

Fig. 6. Influence of change of gasifier's efficiency as well as heat and power generation efficiency of the engine for the overall efficiency of the installation.

4. Conclusion

Development of energy technologies is directed towards development of innovative, ecological solutions that enable highly efficient production of energy carriers. This problem concerns both large scale energy systems as well as medium and small scale distributed units.

Currently, for the range of small and medium power size units, one of the most intensively developed technologies that enable highly efficient generation of heat and power, both from energetic and environmental points of view is gasification of solid fuels. This technology enables production of a combustible gas from solid fuels, i.a. coal, biomass, which after cleaning can be effectively combusted in highly efficient cogeneration units based on piston engines. This provides opportunity for generation of power as well as heat from process of cooling down of high temperature flue gases from the engine, units of its cooling as well as high temperature process gas during its cleaning.

The article presents the issue related to integration of a gasification installation with a selected district heating installation with changing demand for power, ie. from 5 MW to 44 MW. In order to guarantee parameters of the heating water for a selected unit annually, as well as to fulfil the benchmark of CO_2 emission under the level of 550 g/kWh, it is necessary to feed the gasifier with 2 313.6 kg/h of fuel. Mass fraction of biomass and coal in the blend is equal to 71.7% for biomass and 28.3% for coal. Under assumed efficiency of gasification reactor 63.0% respectively efficiency of power and heat generation of the engine η_{elSG} = 37.7% and η_{hSG} = 49.2%, the overall efficiency of the installation is equal to 69.63%.

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