MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION
ŚRODKOWO-POMORSKIE TOWARZYSTWO NAUKOWE OCHRONY ŚRODOWISKA
Annual Set The Environment Protection
Rocznik Ochrona Środowiska
Volume/Tom 18. Year/Rok 2016 ISSN 1506-218X 1007-1017

Energy Production from Biomass in a Trigeneration System

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1. Introduction

Negative phenomena caused by combustion can be overcome by sensible energy management which takes into account economic, social, as well as environmental needs (Cholewa & Pawlowski 2009, Udo & Pawlowski 2010, Pawlowski 2009, Pawlowski 2013). Examples of such friendly technology are already numerous. At present, the wind (Jarzyna et al. 2014, Jarzyna 2011) and photovoltaic (Niechaj 2008) power industries develop dynamically. Their widespread application in smart grid structures enables constant advances in the technology of power electronics and smart metering (Zielinski et al. 2015a, Zielinski et al 2015b). In addition to these technologies, there are other interesting and innovative solutions which utilize biomass (Huang et al. 2011; Stepniewski & Pawlowska 1996, Pawlowska & Siepak 2006; Staszewska & Pawlowska 2011, Montusiewicz et al. 2008). Biomass can be used in various modern technologies, ensuring high efficiency and low emissions of harmful gases.

Most of the current problems involving energy shortages are due to the lack of its efficient and prudent usage. Power network failures in the summer months which in recent years have occurred in both the rich United States and developing India are a clear result of this. These failures occurred largely due to an overload of the energy system caused by a large number of air conditioners working simultaneously. Energy consumption for cooling can, however, be limited. This is facilitated by the development of new technologies, which is referred to as trigeneration.

The application of these technologies reduces the number of necessary changes and lightens the burden on the power system.

The article presents the concept of associating biomass fuel energy with trigeneration. It explains important aspects of trigeneration and the technology of obtaining energy from biomass. Attention has been paid to the effect of energy saving, environmental protection and an extremely important social aspect related to the creation of new jobs.

The final result of the work is showing the benefits of using the trigeneration system instead of separate production of heat, cooling and electricity. The study highlights the positive impact of these technologies on the development of local labour markets, which are conducive to building deeper relationships and the growth of the social wealth of the society.

2. The concept of trigeneration

Trigeneration is a simultaneous or alternating production of three products of different classes of power from a single primary energy source. These products comprise electricity, as well as heat with high-temperature generation and low-temperature production of cooling. Such systems are defined as Combined Cooling, Heat and Power (CCHP) (Wu & Wang 2006).

The interest in the technology is growing. This is because the efficiency of the trigeneration is much higher in comparison to the individual production of each of these forms of energy. It is also higher than the efficiency of co-generative technologies, i.e. combined production of electricity and heat.

The higher efficiency of combined energy production systems results from the fact that the heat in the electric power systems considered is a byproduct and used for heating the thermal energy carriers in CHP units (Filipek & Jarzyna 2012). On the other hand, in CCHP systems it is managed both in thermal processes and for the production of cold. This limits the number of energy transformations, thereby improving the overall energy efficiency of the process.

The main benefit associated with trigeneration constitutes primary energy savings, which can even approximate 60% (Chicco & Mancarella 2006a). In trigeneration systems producing the same amount of cooling requires less fuel than in separate generation system. The trigeneration process is schematically shown in Figure 1.

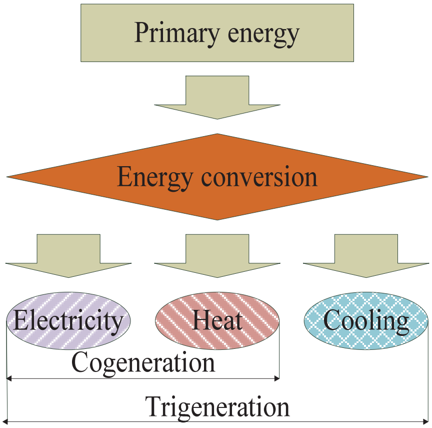

Fig. 1. Combined production of electricity, heat and cooling
Rys. 1. Skojarzona produkcja energii elektrycznej, ciepła i chłodu

The ability to flexibly manage the trigeneration processes and adapt production to the needs of the recipient is an important feature. For example, utilizing trigeneration is justified when the heat recovered outside the heating season is used to for air conditioning. For this reason, it is important to simultaneously determine the need for all types of energy. Production of cold should have a distributed nature. It can be localised in farming-and-food industry plants, office and hotel centres, hospitals and spas, as well as residential buildings (Atănăsoae 2012, Cardona & Piacentino 2003, Huang et al. 2011). Although the fragmented structure is a certain inconvenience, it can yield positive results due to the certain environmental and social aspects. They are discussed in the final chapters of the article.

2.1. Examples of technical solutions in trigeneration

Total or partial replacement of conventional fuels with renewable sources of energy in trigeneration systems could bring additional savings and environmental benefits.

Considering the renewable energy market, employing technical solutions on a small and medium scale is the most rational approach. Depending on the logistical capabilities of biomass transport, the largest systems reach the capacity of approx. 2 MW. The least economically justified units reach 35-75 kW power (Obernberger & Thek 2008). Especially in Poland, the idea of building small and medium-sized installations is justified by the general availability of biomass. Trigeneration power stations should be localised in areas abundant with biomass and with demand for electricity, heat and cold. In order to make an optimal decision regarding the construction of a trigeneration installation, the analysis of key technological and energy issues is required.

In this case, a thorough selection of energy consumers – who would ideally also be fuel suppliers – is needed. An example includes carpenters who use electricity to power appliances and lighting, and heating and cooling for technological purposes, at the same time producing sawdust, shavings and other wood waste from wood processing which can be used as fuel. This shows that trigeneration systems powered by biomass may become an alternative technology for companies with a simultaneous demand for electricity, heat and cold, in order to maximise savings of energy resources.

In this paper we analyse two possible technical solutions for trigeneration systems using biomass as fuel:

1) *The combustion of biomass in trigeneration*

Figure 2 shows a schematic biomass trigeneration system that can be used by a wood processing company. In this case, the fuel consists of waste generated during wood processing: sawdust, wood flour, wood wool and chips and other waste. Biomass is fed to the combustion chamber. During the combustion of fuel in a heat exchanger, water is heated to a high temperature resulting in steam, which is then expanded in a turbine coupled to an electric generator. The water vapour condenses and the condensate is fed back to the boiler.

Electricity produced in this process, is consumed on site to power appliances and lighting, and the unused surplus is fed back into the grid. In turn, the steam is used for production equipment in industrial processes, and the hot water system supplies heat via heat exchangers for central heating and hot water. Absorption refrigerators used to generate cold for technological purposes are powered by steam and fumes.

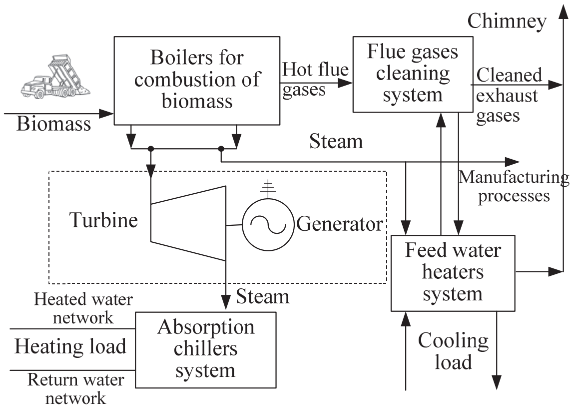

Fig. 2. Exemplary diagram showing the biomass combustion in a trigeneration system
Rys. 2. Przykładowy schemat spalania biomasy w układzie trójgeneracji

2) *Gasification of biomass in a trigeneration system*

Figure 3 shows a scheme of the gasification of biomass in a trigeneration system. Such a system can be used in enterprises where there is simultaneous demand for electricity, heating and cooling.

Biomass in a gas reactor is gasified in the presence of air. The generated synthesis gas is then passed through an integrated cleaning system and gets into the combustion chamber as fuel. The resulting exhaust gases drive the turbine coupled with an electric generator. The waste heat discharged from the water jacket system, as well as the heat coming from the flue gas, is consumed for heating and air conditioning.

Similar technical solutions have been applied in practice (Huang et al. 2011, Maraver et al. 2013), and during many years of work they have demonstrated a high overall yield of a trigeneration system as well as proved their socio-economic and ecological benefits.

The gasification process causes fewer operational problems and can be used in small energy production systems localised, for instance, in the countryside. If biomass is available in sufficient quantity, without the use of precious wood and threatening forests, the gasification process can be employed in the production of all types of energy in rural areas, where it can be applied to power irrigation pumps and machines used in food production.

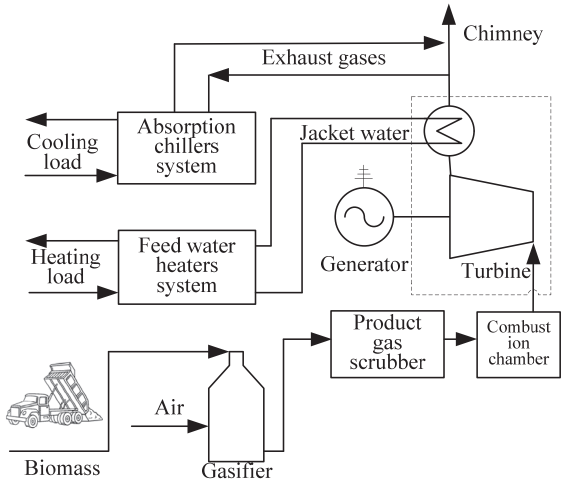

Fig. 3. Exemplary diagram showing the gasification of biomass in a trigeneration system
Rys. 3. Przykładowy schemat zgazowania biomasy w układzie trójgeneracji

2.2. Energy efficiency of trigeneration systems

One of the possibilities of demonstrating how primary energy contained in the fuel is used, is energy efficiency. Energy efficiency is the reduction of primary energy consumption, which can be achieved by changing the final consumption of energy by means of technological or economic modifications, providing the same level of comfort and services.

The most commonly used indicators for analysing the trigeneration system include:

- Energy Utilisation Factor (*EUF*)(Chicco & Mancarella 2006b),
- Trigeneration Primary Energy Saving (*TPES*)(Atănăsoae 2012),
- Power to Heat Ratio (*PHR*), (Atănăsoae 2012).

The above-defined indicators form the basis for an analysis of energy efficiency and primary energy savings.

By using these ratios one can compare the energy efficiency of energy production in trigeneration systems during various processes of biomass incineration. The values of energy efficiency indicators for these two processes are shown in Table 1.

Table 1. Comparison of energy efficiency of combustion and gasification
Tabela 1. Porównanie efektywności energetycznej spalania i zgazowania

Process	Combustion of biomass	Gasification of biomass
Energy Recovery	12380 kJ/kg	5835 kJ/Nm^3
Consumption of biofuels for energy production	56,8 kgpu/GJ	42,6 kgpu/GJ
PHR	0,6-0,7; (η_{el} > 38%)	0,5-0,7; (η_{el} > 30%)
EUF	65%	50-60%

On the basis of the data on the calorific values of different types of biomass given in the literature (Maj 2015, Stolarski et al. 2013b) it is possible to determine the energy recovery in combustion and gasification. As can be seen from Table 1, the calorific value produced during the gasification of the synthesis gas is at times similar to the lower calorific value of biomass. In addition, the gasification process significantly affects the reduction of the amount of fuel required to produce a unit of energy. Therefore, combustion and gasification offer similar conversion of biomass into usable energy.

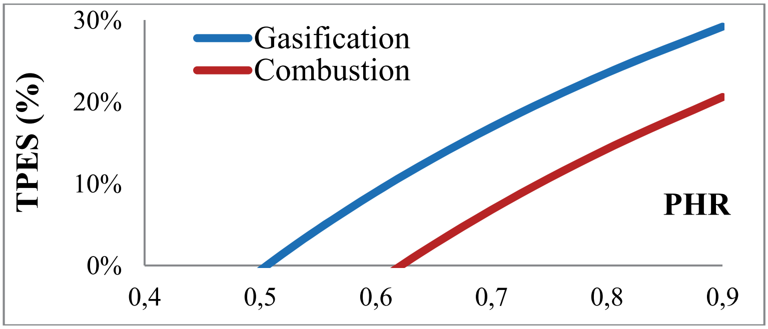

Fig. 4. Trigeneration primary energy saving depending on Power to Heat Ratio
Rys. 4. Oszczędność energii pierwotnej w systemie trójgeneracji w zależności energii do ciepła

Using the *TPES* index allows to determine primary energy savings depending on the *PHR* ratio of electricity to heat. As seen in Figure 4, trigeneration systems may be advantageous if the power to heat ratio is in the range of 0.5-0.75. Accordingly, the trigeneration systems in which the production of electricity, heat and cold involves the combustion process can be advantageous when the *PHR* is higher than 0.6. Thus, it follows that the energy efficiency for electricity generation in partial trigeneration must be greater than 38%. For trigeneration systems using gasification the system starts being effective at *PHR* greater than 0.5, i.e. when the partial energy efficiency for electricity generation in trigeneration is more than 30%.

It is believed that the selection of appropriate parameters of electrical, heating and cooling load in combined production has an impact on energy efficiency. If the partial energy efficiency of the production of electricity is low, trigeneration may not exhibit effectiveness when compared to the separate production system. Furthermore, this analysis might help to optimise the combined production of energy. A properly selected power to heat ratio (*PHR*), depending on demand, may become a useful tool for optimising trigeneration processes, and allow to achieve the best energy efficiency of a trigeneration system in selected working conditions.

3. Summary

Trigeneration technologies based on biomass combustion and gasification offer a huge potential for reducing CO_2 emissions, since they are based on renewable energy sources. The advantages of such a system are, above all, saving primary energy, using excess energy and waste heat, reducing energy losses, reducing emissions and increasing efficiency of the entire energy system. From an energy-saving point of view, the overall annual primary energy utilisation rate EUF (amount of chemical energy of fuel actually converted to useful energy) in trigeneration should not be less than 60%, and should preferably exceed 80%.

Typical areas of application of trigeneration power plants using biomass are wood-processing industry, local energy systems, as well as a variety of industries with a high demand for heat and cold. Due to the relatively low energy density of biofuels, CCHP technologies using biomass should mainly be used in decentralised systems. An advantage of such systems, situated as close to the receiver as possible, is that the transmission losses are ignored.

The use of biomass as an energy source can reduce the consumption of fossil fuels while providing environmental benefits. In addition, the combination of these technologies can bring additional profits in the form of cost-effective use of local fuels.

Proper segregation and maximum utilisation of the huge energy resource in the form of waste biomass creates the potential for an effective waste management system, combined with the production of electricity, heat and cold.

Efficient use of natural resources, accompanied by a simultaneous production of electricity, heat and cold, is justified if it provides a more effective use of primary energy, in comparison to the conventional systems of energy production in the selection of appropriate parameters of electricity, heating and cooling load.

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Produkcja energii z biomasy w systemie trójgeneracyjnym

Streszczenie

Wytwarzanie w oddzielnych procesach energii elektrycznej, ciepła i chłodu to duża niegospodarność energetyczna. Zdecydowanie efektywniej i lepiej dla środowiska jest produkować te wszystkie trzy formy energii w jednym procesie technologicznym, w procesie trójgeneracji. Takie działanie umożliwia elastyczne zarządzanie parytetami energii w zależności od aktualnych potrzeb. W skojarzeniu z biomasą jako źródłem energii pierwotnej, daje wzmocnienie korzyści ekonomicznych, środowiskowych i społecznych. Artykuł wyjaśnia tę nowoczesną ideę wskazując, że taka droga rozwoju może stanowić ważny etap w budowie inteligentnych systemów energetycznych, ochronie środowiska i wzmocnieniu więzi społecznych.

Słowa kluczowe:
trójgeneracja, CCHP, zarządzanie energią, biomasa, zgazowanie, spalanie, integracja lokalnych społeczeństw, rozproszona trójgeneracja, inteligentne systemy

Keywords:
trigeneration, CCHP, energy management, biomass, gasification, combustion, integration of local communities, distributed trigeneration,
smart energy systems