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Experimental and economic study of small-scale CHP installation equipped with downdraft gasifier and internal combustion engine

Witold Elsner [a], Marian Wysocki [a], Paweł Niegodajew [a,*], Roman Borecki [b]

[a] Czestochowa University of Technology, Institute of Thermal Machinery, al. Armii Krajowej 21, 42-200 Czestochowa, Poland
[b] Institute of Research & Machinery Implementation Ltd., ul. Sokola 4, 42-256 Olsztyn, Poland

HIGHLIGHTS

- Innovative design of downdraft gasifier with internal heat exchanger.
- Stable working conditions regardless lower calorific value of a fuel.
- Self-adjustment of gasifier operation under rapid changes in gasifying agent load.
- The most profitable scenario of CHP plant operation is proposed.

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ABSTRACT

This paper concerns the experimental and numerical analysis of a combined heat and power (CHP) installation equipped with a biomass downdraft gasifier, gas purification system and gas piston engine. The numerical studies were aimed at identifying waste heat in the CHP installation for further utilisation. In turn, a new innovative method of heat recovery inside the gasifier was proposed and subsequently applied in the experimental CHP installation. The newly developed facility is able to produce up to 75 kWe of electrical power. An extensive parametric study was performed under the steady and unsteady facility operation and was supplemented by economic analysis of the process. The main objective of the study was to examine the possibility of sewage sludge gasification and the impact of produced syngas quality on gas engine performance. During the investigation a number of different types of biomass were investigated including wood pellets, sewage sludge and their blends. The results showed a stable operation of the CHP facility in terms of produced syngas load, calorific value and content – even when dried sewage sludge was used alone. Results indicate that a 40/60% blend of wood pellets with sewage sludge is recommended, which allowed the lower heating value (LHV) of 4.45 MJ/Nm^3. Additionally, it was confirmed that the fixed bed gasifier is able to self-adjust to temporary changes in gasifier agent load.

The economic analysis was performed taking into account policies and regulations in the Polish energy market sector. The study showed that it is more profitable to use the generated electricity and heat for its self-consumption rather than selling it on the market. Even with the supporting policies the payback time is not less than about eight years. Taking into account calorific value and limited local biomass availability, it seems justified that the described CHP installation is suitable for decentralised power generation such as small farms or horticultural businesses, where the produced electricity and heat can be sufficiently utilised. This technology also contributes to reduction of CO_2 emissions into the atmosphere, which is one of the most problematic issues for energy sector today.

1. Introduction

Current trends in energy and environmental sciences show an on-going global effort to replace fossil fuels with renewable energy sources. Particularly interesting are biomass conversion methods (including biomass wastes) which represent a valid alternative to fossil fuels [1]. Wide biomass availability and its largely uniform distribution put bio-energy production ahead of many other renewable energy sources. Diverse biomass types are commonly available as agricultural waste, food waste, industrial wastewaters and sewage sludge. All are generated in large volumes and have already found their usefulness as non-conventional energy source

* Corresponding author.
E-mail address: niegodajew@imc.pcz.czest.pl (P. Niegodajew).
URL: http://www.imc.pcz.pl (P. Niegodajew).

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in a number of countries worldwide. In contrast to wind and solar-based approaches, energy production technologies based on biomass are independent of weather conditions and only slightly depend on the location [2,3]. Biomass is easily storable and transportable, helping this fuel type to be ranked among the top four energy sources in terms of world final consumption. Consequently, a continuous dynamic progress in energy production using biomass can be observed. For instance, the global total net biopower generation increased from 60.5 TW h in 2011 to 65.0 TW h in 2012 [4]. Due to the fact that biomass is also characterised by a low calorific value and limited local availability, its use is justified in smaller sized power plants located near the biomass generation sites or where logistic activities (collection, transport, storage) are available and economically justified [5].

Particular attention should be paid to sewage sludge, which represents a biomass waste group that is produced as a by-product in municipal wastewater treatment plants. As a consequence of rapid urbanisation, the increased generation of municipal waste and sewage sludge management are now serious global environmental problems [6]. For example, as can be seen from Fig. 1, the production of dry sewage sludge from municipal treatment plants in Poland between 2000 and 2016 significantly increased from 359.8 to 610 thousand tonnes [7] and only 17% is currently thermally transformed [8]. Out of this 17%, even less is transformed to usable energy. Sewage sludge in Poland usually contain large amounts of pathogenic organisms as well as high concentrations of heavy metals and toxic substances [9]. This is in striking contrast to Western European countries, which invested in incinerator plants many years ago. However, recently a restrictive legislation was introduced on the 1st of January 2016, which prohibits landfill waste disposal characterised by calorific value greater than 6 MJ/kg [8]. This restriction also applies to sewage sludge.

Among a number of technologies for energy production from biomass, gasification may be regarded as the most promising option. This approach, especially in small-scale plants with electrical power output less than 10 MW, provides an attractive alternative to other existing techniques such as biomass combustion [10] because it can accept a wide variety of fuels. Gasification reduces the carbon-to-hydrogen (C/H) mass ratio which increases the calorific content and as a result increases the energy density of produced gas [11]. The syngas resulting from the gasification process is more versatile in use than the original solid biomass [12]. Biomass gasification is a simple and economically viable process enabling the production of thermal or electrical energy. It has been

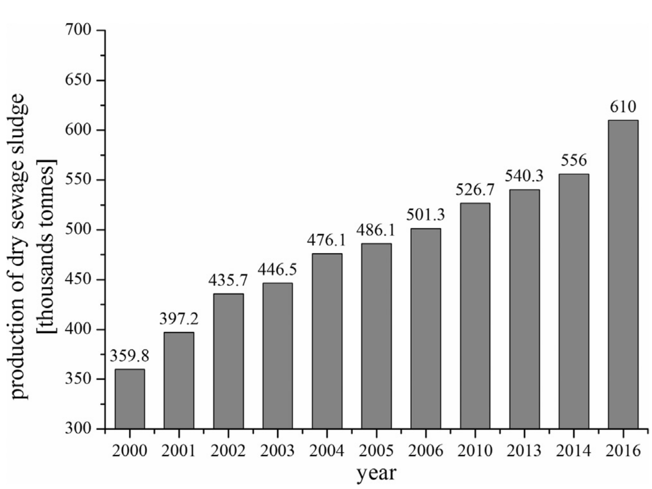

Fig. 1. Generation of dry sewage sludge among the years in Poland with the forecast for 2016 [7]

proven that the gasification process is not limited to a particular feedstock or a specific product. It is also flexible towards the treatment of biomass wastes that may be toxic or contaminated and can be used to generate a usable syngas of diversified composition [13]. The syngas content and its calorific value depend on the gasifying agent, which can be air, oxygen (O_2), steam (H_2O) or carbon dioxide (CO_2). In most cases the biomass is gasified in atmospheric systems rather than in pressurised installations [14]. Consequently, gas produced from air gasification is characterised by the lower heating value (LHV) of around 4–7 MJ/Nm^3 mainly due to a high nitrogen content. Biomass gasification also contributes to the reduction of CO_2 emissions which is another major global environmental problem next to the production of sewage sludge [15,16].

Several types of gasifier constructions are available today, which can be divided into two groups: with fixed or fluidised beds. The detailed description of individual configurations can be found in the following papers [17–21]. It has been shown that there is no significant advantage of either the fixed bed or the fluidized bed reactors and individual benefits mainly depend on the physical composition of the gasifier input [22]. In one of the recent review papers [23] it was concluded that the optimal choice of a gasification technology for a given task depends on a number of factors, including feed stock availability, know-how, project economy, local politics, environmental concerns and life cycle assessment.

Due to limited local availability and high transportation costs of biomass, the best technology for gasification that is suitable for small scale applications seems to be the application of fixed bed downdraft gasifiers. According to Basu [24] a typical thermal power plant using this type of gasifier produces power ranging from 0.5 MWt to 10 MWt which makes the technology suitable for decentralised power generation and distribution to remote residential housings that are deprived of grid electricity [22]. Consequently the review paper of Singh [25] strongly recommends promotion of gasification units for rural electrification. Moreover, biomass gasification in the fixed bed downdraft reactors is also currently considered to be one of the most mature technologies [26]. Whilst the syngas produced using such an approach is characterised by a lower calorific value than the one generated with the use of a countercurrent gasifier, it contains evidently less dust and tar [27]. Tar formation during the biomass gasification process is a serious problem. Tar is a thick and a viscous liquid containing heavy aromatic hydrocarbons (toluene, naphthalene and phenol with many other aromatics comprising of up to seven benzene rings as secondary components) and often a high content of heavy metals [28–30]. A number of tar removing/reducing methods are described in the following publications [31–38].

The results of theoretical, experimental and numerical investigations of downdraft biomass gasifiers are presented in a large number of recent papers. For instance, experimental research has explained the impact of a number of parameters on gasifier performance and operation:

- different feedstock types [39–43] and their properties [44],
- gasification temperature [19,45,46],
- equivalence ratio (ER) defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio [39,47],
- particle/pellet size [48,49],
- moisture content in biomass [50],
- different gasifying agents [45,51],
- high gasifying agent temperature [52],
- pressure drop [53,54],
- air flow rate [55] and heat recovery systems [55,56]

There are also a number of publications using mathematical modelling to attempt to describe the main chemical and physical processes within the gasifier reactor [57–62].