



Method of Selecting a Biomass Gasification Boiler, Thermal Energy Storage and Fuel Demand for a Residential Building

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Abstract: Selecting a biomass gasification boiler, thermal energy storage, and fuel for a residential building requires considering several important elements to ensure the heating system is efficient, economical, and tailored to the user's needs. The article presents issues related to the modernization and use of a heat source, such as a gasification boiler cooperating with thermal energy storage. The above-mentioned elements of the installation are characterized, and their advantages and disadvantages are indicated. The article's main goal was to propose a calculation method for selecting a biomass gasification boiler and a heat buffer for heating existing and newly designed buildings. The method considers the daily demand for thermal energy of the building and the selection of the boiler, not only according to power but also the size of the loading chamber. In addition, a method for calculating the daily fuel demand is presented. The proposed method will significantly enable correct boiler-buffer configuration and reduce the time required to operate the heating system.

Keywords: biomass, gasification boiler, thermal energy storage, thermal modernization

1. Introduction

Ensuring energy security, independence from fossil fuels, and reducing greenhouse gas emissions encourages using renewable energy sources (Zhang et al. 2022). Functioning in European structures, Poland should pursue a policy consistent with the European Union strategy based on a constant increase in the share of energy obtained from renewable sources and striving to reduce greenhouse gas emissions (Kubicka 2019). Poland is a country that enjoys one of the largest bioenergy opportunities in Europe, where renewable energy is based on biomass resources (Igliński et al. 2022). According to Directive 2009/28/EC, biomass means the biodegradable part of products, waste, or residues of biological origin from agriculture, forestry, and related industries, including fisheries and aquaculture, as well as the biodegradable part of industrial and municipal waste. Any type of biomass can be used for energy purposes, provided that food security is ensured first (Jarosz 2017).

The growing demand for energy, environmental pollution caused by burning fossil fuels, and national and EU regulations mean that more and more attention is being paid to the possibilities of obtaining biomass for energy purposes. Many authors have mentioned how important the costs of maintaining single-family houses are in the household budget in terms of ensuring the right amount of energy. These costs include heat losses related to heating and ventilation (Baranowski & Ferdyn-Grygierek 2013, Kępa, 2014). The above aspects directly affect the operating costs of designed and selected devices (Gładyszewska-Fiedoruk & Bobryk 2017). One way to reduce house maintenance costs is to modernize the heating system. Central heating installations are becoming more advanced, using modern materials and solutions. Various generating units are available that cooperate with automation and use many types of alternative fuels. Most heating systems used in residential construction are based on water heating using a solid fuel boiler as a heat source.

Modern heating technologies are gaining importance in the era of rising energy costs and the need to reduce carbon dioxide emissions. A heat buffer is a key element of many advanced heating systems, which allows for effective thermal energy management in residential, commercial, and industrial buildings. A heat buffer is nothing more than a storage tank in which thermal energy is stored as hot water (Burzyński 2022). It allows for more efficient use of various heat sources, such as solid fuel boilers, biomass boilers, heat pumps, solar collectors, or heating systems powered by electricity. The buffer allows for the storage of surplus heat produced during periods of lower demand, and it is used when this demand increases. This solution not only improves thermal comfort but also reduces operating costs and extends the life of heating devices. Thanks to the growing popularity of renewable energy sources, such as gasification boilers or solar collectors, the use of a heat buffer is becoming more and more universal. This device allows effective energy stor-



age and the optimization of the entire heating system (Stalmark 2024). Due to the upper supply of the buffer, the water is arranged in layers and is not mixed (Dziubela 2023).

In the face of climate change and global energy challenges, thermal efficiency and energy storage are becoming particularly important. Thanks to the buffer, biomass boilers can operate in optimal conditions, which minimizes the frequency of their extinguishing and re-ignition. This, in turn, leads to the extension of the boiler's service life, reduced service costs, and reduced harmful emissions into the atmosphere. In addition, the buffer allows for flexible heat supply to the heating system, regardless of the current operation of the boiler, which is particularly important in the case of uneven heat demand, e.g., during the day (Nantka 2006, Pieńkowski et al. 1999). This is one of the basic conditions for ensuring thermal comfort, the parameters of which are: indoor temperature, air velocity in the room, and air humidity (Fanger & Toftum 2002, Gładyszewska-Fiedoruk & Krawczyk 2015, Kowalczyk 2010, Toftum et al. 2004, Xiaowen et al. 2024).

The work aims to indicate the calculation method for selecting a wood gasification boiler, a heat buffer, and the fuel demand for heating purposes for a residential building.

2. Description of the Calculation Method

Biomass is currently used by households for heating purposes and burned by professional energy. The greatest economic and ecological benefits can be achieved by using biomass as close to the places where it is obtained or processed (Sharma et al. 2020, Duda-Kękuś 2011). Wood, briquettes, pellets, and straw are used in boiler rooms and combined heat and power plants with high energy efficiency (Tezer et al. 2022). When selecting an ecological heating source based on biomass, it is important to use it according to the principles provided by the manufacturer, which will allow for long-term, failure-free operation with minimal environmental damage (Klimosz 2024). The costs of investment or modernization should be analyzed, all advantages and disadvantages considered, and the system should be adapted to existing conditions. A poorly selected source, e.g., oversized, will not ensure effective, rational energy use.

The demand for heat energy for each building is different. This results from, among other things, the building materials used, thermal insulation and the individual requirements of the household members. Due to their compact development and smaller glazing, multi-family buildings need less heat energy than single-family houses. Precise heat calculation allows you to determine how much energy the building needs to maintain the desired internal temperature, regardless of external conditions (Orłowska 2023). Precise determination of the building's demand for heat energy is time-consuming and, in some cases, difficult to determine, especially when the buildings do not have construction documentation. In the above cases, the unit heat demand for 1 m² in the heating season of a particular type of building can be used, amounting to (Gawlikowski 2021):

- old single-family housing (before 1990) – 150-170 [kWh/m²],
- old single-family housing with windows replaced with double-glazed ones – 120-150 [kWh/m²],
- old single-family housing with wall insulation and replacement of windows and roof – 80-120 [kWh/m²]
- energy-efficient single-family housing – 50-70 [kWh/m²],
- passive houses – 10-15 [kWh/m²],
- old multi-family housing – 100-130 [kWh/m²],
- old multi-family housing with insulation – 50-80 [kWh/m²],
- energy-efficient multi-family housing – 30-50 [kWh/m²].

It should be remembered that the above data can be treated as general guidelines. However, detailed calculations of the heat demand (HDR) of a building should be preceded by calculations performed by a person with the appropriate knowledge and qualifications in this field. This method is accurate but complicated and requires knowledge of construction and energy. Thanks to these calculations, we can determine how much heat is needed and what heating power should be used, and it is possible to determine the energy class of the building.

2.1. Gasification boiler

A boiler is an energy device in which the chemical energy of the fuel is converted into thermal energy in the combustion chamber. Part of this energy is transferred to water, and part is released into the atmosphere with exhaust gases. The useful effect of the conversion is an increase in the temperature and thermal energy of the water. The combustion of biomass in a gasifying boiler takes place in a two-stage process called gasification (Champion & Grieshop 2019). The course of the wood gasification process in the boiler is shown in Fig. 1.

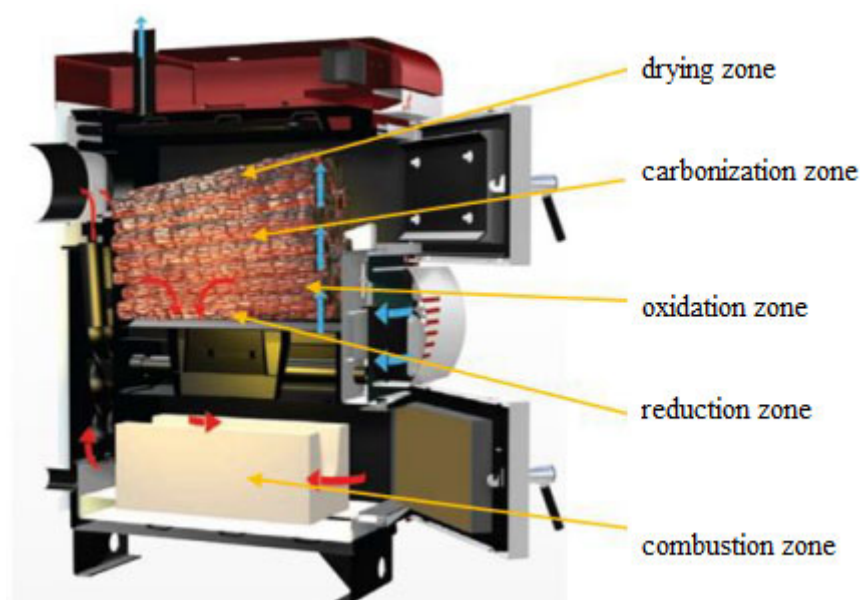


Fig. 1. Wood gasification process stages (Ojczyk 2020)

The entire process takes place in one space divided into five zones, and the final effect is heat energy generation. First, in the pyrolysis process, water contained in the fuel is released from wood or other biomass; this is the drying process. Then, gasification (carbonization) takes place. This is a gradual increase in the temperature of the wood, which results in the release of gas from it. The gas produced from biomass is a flammable mixture of gases, lighter than air, which, due to the presence of methane and hydrogen, is characterized by flammable properties. The gasification of biomass takes place inside the upper chamber, then the gas penetrates the high-temperature layer and finally reaches the burner nozzle, where it is mixed with air. The next stage is classic combustion, which takes place at a temperature of up to 1300°C, during which heat is released (Konieczna et al. 2022, Matuszek 2018). Gasifying boilers are boilers with manual fuel supply, with lower combustion, achieving higher efficiency than boilers with upper combustion. According to the standard transferring the European standard EN 303-5:2012, they should be operated with a storage tank. This standard also specifies the minimum safe capacity of the heat storage, which is 50 l per 1 kW of boiler power. In addition, it characterizes boilers in terms of pollutant emissions, such as carbon monoxide (CO), dust, and organic pollutants (OGC) (Dz.U.2017.1690 2020). Requirements for biomass boilers in terms of emission limit values are presented in Table 1. The condition for the proper functioning of the gasifying boiler is to maintain the required high temperature and constant heat collection, and this can be ensured by equipping the central heating installation with a storage tank (Lewandowski & Rymus 2013, Mishra et al. 2021). For example, a general connection diagram of a gasification boiler with a heat buffer is shown in Fig. 2. When configuring the heating set, it is necessary to consider the requirements for securing the installation against pressure increase recommended by the manufacturers of both boilers and accumulation tanks.

Table 1. Pollutant emission limit values according to PN-EN 303-5:2012 for biomass boilers

Fuel supply method	Nominal thermal power [kW]	Limit values for pollutant emissions (mg/m ³ at 10% O ₂)								
		CO			OGC			Dust		
		Class 3	Class 4	Class 5	Class 3	Class 4	Class 5	Class 3	Class 4	Class 5
Manual	≤ 50	5000	1200	700	150	50	30	150	75	60
	50-150	2500			100					
	150-500	1200			100					
Automatic	≤ 50	3000	1000	500	100	30	20	150	60	40
	50-150	2500			80					
	150-500	1200			80					

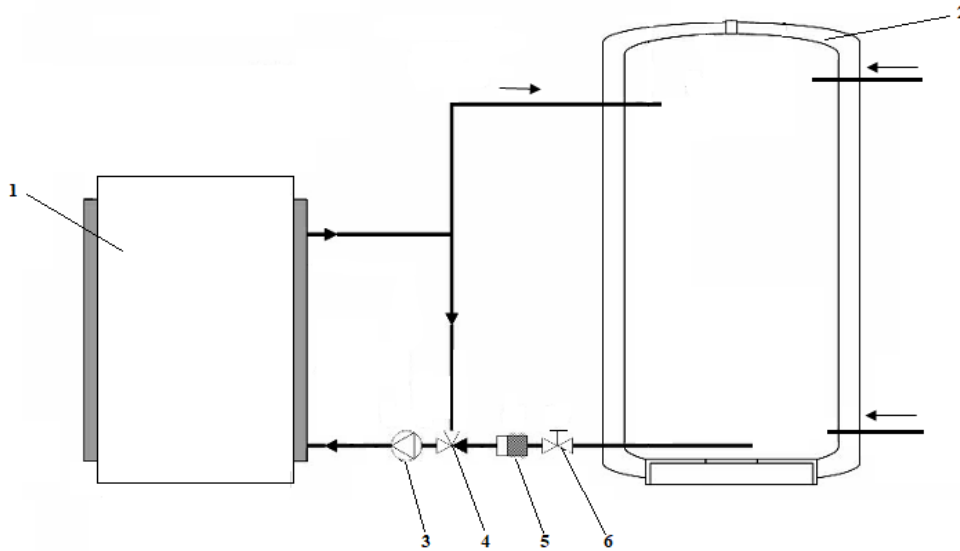


Fig. 2. Gasification boiler connection diagram with buffer: 1 – boiler, 2 – buffer, 3 – circulation pump, 4 – boiler protection temperature valve, 5 – check valve, 6 – shut-off valve

2.2. Buffer and boiler selection

The capacity of the tank accumulating thermal energy will largely depend on the energy demand of the building. With the building's energy demand calculations prepared by a qualified person, the buffer capacity and boiler power can be precisely determined. If we do not have such information, we can calculate the thermal energy demand using the following formula (Gawlikowski 2021):

$$Q_d = S_u \cdot q_d \text{ [kWh]} \quad (1)$$

where:

Q_d – annual (seasonal) demand for thermal energy for the building [kWh],

S_u – building area [m^2],

q_d – annual demand for thermal energy for 1 m^2 [kWh/m^2].

The daily demand for thermal energy, which will be delivered to the building via water, must be calculated to determine the buffer capacity. For this purpose, the following formula should be used:

$$E_w = \frac{Q_d}{t} \cdot 3600 \text{ [kJ/day]} \quad (2)$$

where:

E_w – thermal energy of water [kJ],

t – duration of the heating season [days].

After calculating the required daily thermal energy of water for the heating season, the buffer capacity is determined using the formula:

$$V_B = \frac{E_w}{c_w \cdot \Delta T} \text{ [dm}^3\text{]} \quad (3)$$

where:

V_B – buffer capacity [dm^3],

c_w – specific heat of water [$\text{kJ}/\text{kg} \cdot \text{K}$],

ΔT – increase in water temperature in the buffer [$^{\circ}\text{C}$].

The appropriate buffer capacity is necessary to select a tank that will store hot water heated by the boiler and allow for its moderate and controlled use to ensure thermal comfort in the building around the clock. The capacity of the hot water buffer is important for the efficient operation of heating systems, energy storage, and ensuring stable access to hot energy, which contributes to improving energy efficiency and reducing heat losses. The buffer acts as a storage for excess thermal energy in the form of hot water, which can be:

- used and stored when the heat source is active, the heating demand is lower than the source power,

- stored when the source is active, the heating demand is at a later time,
- used when the source is active, but the demand is higher than the source's instantaneous power,
- used when the source is active, the demand is equal to the source power,
- used when the source is not active but there is a heating demand.

Knowing the daily demand for thermal energy and the buffer capacity, it is necessary to calculate the required fuel mass needed to obtain a given amount of energy according to the formula:

$$m_{PB} = \frac{E_w}{G_e \cdot 3600} \text{ [kg]} \quad (4)$$

where:

m_{PB} – fuel mass needed to heat water in the buffer [kg],

E_w – thermal energy of water in the accumulation [kJ],

G_e – energy value of wood [kWh/kg].

The calculated fuel mass will depend largely on the energy value of the tree. The energy values of selected tree species are presented in Table 2.

Table 2. Energy values and density of selected tree species (Kowalczyk 2016, Lenartowicz 2023)

Wood type	Density [kg/m³]	Energy value at humidity 20%		
		[kWh/m³]	[kWh/mp]	[kWh/kg]
Coniferous wood				
Spruce	430	2100	1500	3.0
Fir	410	2200	1550	3.4
Larch	550	2700	1800	3.2
Pine	510	2600	1900	3.3
Deciduous wood				
Birch	640	2900	2000	4.0
Elm	640	3000	2100	4.2
Beech	680	3100	2200	4.3
Ash	670	3100	2200	4.0
Oak	670	3100	2200	4.1
Hornbeam	750	3300	2300	4.3

As a result of the large temperature difference between the buffer and the environment, heat loss occurs, referred to as standby losses. For buffers available on the market with a capacity of 600 to 1200 liters, this loss is about 2 kWh/day (Dziubela 2023, Klimosz 2024, Stalmark 2024). This amount of energy should be considered when calculating the amount of wood. To calculate the total mass of fuel, the fuel that will cover the standby losses should be taken into account:

$$m_{psp} = \frac{S_c}{G_e} \text{ [kg]} \quad (5)$$

where:

m_{psp} – fuel mass to reduce buffer standby loss [kg],

S_c – buffer thermal energy loss [kWh/day].

Daily fuel demand (m_{pd}) is the amount of fuel used in one day for energy purposes. Correctly calculated, it allows you to estimate costs and manage fuel supplies more effectively. To calculate the daily fuel demand, use the following formula:

$$m_{pd} = m_{PB} + m_{psp} \text{ [kg]} \quad (6)$$

where:

m_{pd} – daily fuel demand [kg].

After taking into account the energy efficiency of the boiler, the m_{pd} is:

$$m_{pd} = \frac{m_{pb} + m_{psp}}{\eta} \text{ [kg]} \quad (7)$$

where:

η – energy efficiency of the boiler [%].

When selecting a wood gasification boiler cooperating with a heat buffer, the volume of the boiler's loading chamber plays an important role. To minimize the daily maintenance of the boiler related to replenishing biomass, it is advisable to obtain the required amount of energy for heating after filling the loading chamber once. For this purpose, after calculating the fuel mass, calculate the fuel volume according to the formula (Francescato et al. 2008):

$$V_p = \frac{m_{p,d}}{\rho_p} \cdot w \text{ [m}_p\text{]} \quad (8)$$

where:

V_p – fuel volume (loading chamber) [m_p],

ρ_p – [kg/m³],

ρ_p – fuel density [kg/m³],

w – conversion factor of cubic meters into cubic meters (m_p) depending on the species and assortment of wood: from 1.43 to 1.75.

When selecting a boiler that works with a heat buffer, special attention should be paid to the calculated heat demand of the building. To ensure comfort in the rooms and the possibility of accumulating energy in the buffer, the boiler power should be:

$$P \geq S_u \cdot q_s \text{ [kW]} \quad (9)$$

where:

P – boiler power [kW],

q_s – heat demand for 1 m² [W/m²].

Using a boiler with a higher power than the calculated thermal demand of the building does not result in its oversizing; it allows it to reach the set temperature in the accumulation tank in a shorter time. When selecting a gasification boiler, the recommendations of the EN 303-5:2012 standard should be taken into account.

3. Conclusions

Due to the high prices of energy carriers, thermal modernization of buildings is inevitable. One of them is the modernization of the heat source. Using an appropriate heating system, including heat storage and a wood gasification boiler, can significantly reduce operating costs and the emission of harmful substances into the atmosphere. This is due to the higher efficiency and performance of modern heating devices.

An important element in favor of modernizing the heat source is high energy efficiency, which brings direct financial benefits to users in the form of lower bills. An additional argument in favor of replacing an inefficient heat source with a new one is investment support, e.g., from the Clean Air, Stop Smog program, which allows for covering part of the modernization costs (NFOSiGW 2024).

The currently used method of selecting a heat buffer for a gasification boiler, as described in the PN-EN 303-5:2012 standard, comes down only to using the appropriate boiler power for the tank volume. The method of selecting a heat accumulator tank proposed by the authors considers the above aspects and the building's demand for thermal energy. In addition, it contains guidelines for calculating the size of the loading chamber in the boiler and the fuel demand. The cooperation of the energy storage and the boiler with an appropriately selected capacity of the loading chamber allows to reduce the amount of time that the heating system user will have to spend on the daily service of the heat source, and the use of such a system becomes more comfortable. The proposed method of selecting a buffer cooperating with a gasification boiler can be used in newly designed buildings and buildings subject to modernization. It allows thermal comfort around the clock and improves the boiler's efficiency, which usually operates at maximum power.

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