PRIMARY ENERGY SAVINGS USING HEAT STORAGE FOR BIOMASS HEATING SYSTEMS

by

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District heating is an efficient way to provide heat to residential, tertiary and industrial users. The heat storage unit is an insulated water tank that absorbs surplus heat from the boiler. The stored heat in the heat storage unit makes it possible to heat even when the boiler is not working, thus increasing the heating efficiency. In order to save primary energy (fuel), the boiler operates on nominal load every time it is in operation (for the purpose of this research). The aim of this paper is to analyze the water temperature variation in the heat storage, depending on the heat load and the heat storage volume. Heat load is calculated for three reference days, with average daily temperatures from –5 to 5 °C. The primary energy savings are also calculated for those days in the case of using heat storage in district heating.

Key words: *heat storage, biomass heating systems, primary energy savings*

Introduction

Currently, fossil fuels such as oil, coal and natural gas represent the prime energy sources in the world (approximately 80% of total use of more than 400 EJ per year). However, it is anticipated that these sources of energy will be depleted within the next 40-50 years. Moreover, the expected environmental damages such as the global warming, acid rain and urban smog due to the production of emissions from these sources have tempted the world to try to reduce carbon emissions by 80% and shift towards utilizing a variety of renewable energy resources which are less environmentally harmful, such as solar, wind, biomass, *etc*. in a sustainable way [1, 2]. The Intergovernmental Panel on Climate Change reported that continued emissions from fossil fuels would lead to a temperature increase of between 1.4 and 5.8°C over the period from 1990 to 2100 [3].

The European Commission, and many other public and private organizations, believes that biomass for power and heat production can play an important role in meeting Europe's "20-20-20" targets: by the year 2020, greenhouse gas emissions should be reduced by 20%, renewable energy sources should represent 20% of Europe's final energy consumption, and energy efficiency should increase by 20%. Biomass is already the most important renewable energy source in Europe with a huge potential for further expansion. The future development of biomass should follow some basic principles such as high conversion

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efficiency, competitiveness and sustainability. The experience proves that the use of biomass to produce heat complies in an optimal way with these principles. Biomass for heat can be used in small scale units for individual houses, in heat contracting projects, in district heating and in the industry. In any case, the supply of high quality biomass, be it firewood, wood chips, pellets or refined wood, is of essential importance for the rapid growth of this market.

Biomass energy offers several significant benefits in comparison to fossil fuels. It is renewable and therefore reduces reliance on nonrenewable fuels and their associated greenhouse gas emissions; it is locally available and therefore creates local jobs and reduces energy use for transport and/or imports; it creates value by recovering the energy in waste that would normally be destined for landfills; finally, it is a low-cost fuel even at current depressed natural gas prices.

Today, biomass contributes about 10-15% (or 45±10 EJ) of this demand. On average, in the industrialized countries biomass contributes some 9.14% to the total energy supplies, but in developing countries this is as high as one-fifth to one-third [4]. According to the world energy council projections, if the adequate policy initiatives are provided in 2025, 30% of the direct fuel use and 60% of global electricity supplies will be met by renewable energy sources [1]. The major source of GHG emissions from a boiler system is carbon dioxide (CO_2) from the combustion of fossil fuels in the boiler. Other minor sources of GHG can include methane (CH_4) from leaks in the natural gas distribution system and CH_4 and nitrous oxide (N_2O) as byproducts of combustion processes [5].

Biomass generally means any biological matter that can be burned for energy, including cordwood, wood chips, sawdust, bark, various other forms of chipped sawmill wastes, and wood shavings or other ground-up wood from wood manufacturing operations. Other, less usual forms of burnable biomass include straw, corncobs, nut shells, seed hulls, pine cones, and some food-processing wastes. Wood pellets are another form of biomass fuel. Unlike most other biomass fuels, pellets are a manufactured product.

Biomass and its combustion have been the subject of a number of studies. Ilić *et al.* [6] presented a review of the energy potential of different types of biomass residues in agriculture and forestry, and the actual state of biomass energy utilization in Serbia. Obernberger *et al.* [7] presented a physical characterization of biomass fuels, together with their chemical compositions, with regard to their combustion behavior. Vallios *et al.* [8] presented a methodology of the design of biomass district heating systems, taking into consideration the optimum design of building structure and urban settlement around the plant. In 2004, Lundgren *et al.* [9] presented their experimental work in the area of developing a furnace suitable for small district heating networks. The fuel was wood-chips. The aim of their study was to evaluate the performance of the combustion chamber during steady-state operation in a complete thermal output range. Turanjanin *et al.* [10] presented their work in developing technology for utilizing bales of various sizes and shapes for energy production. The development started with the design and construction of a small-scale hot water boiler, with thermal power of 50 kW, for combustion of small cubic soya straw bales.

One of the important features of biomass boilers is a need for steady operation. Under steady-state conditions, boiler efficiency reaches maximum, its operating life is considerably prolonged and the ratio between heat generation and CO_2 emission is considered to be optimal. On the other hand, heating system is characterized by a dynamic operation, primarily affected by frequent changes in environmental temperature. For the above reason, a biomass boiler can only be used in a heating system equipped with a heat storage. Heat storage has an important role in terms of the use of energy in buildings, since a lot of energy can be saved in this way. Heat storage takes the surplus heat from a boiler used for heating buildings and stores it. When the boiler shuts off and is no longer actively heating, the heat stored in the heat storage unit can be used to heat the building. Many studies have been made in the field of heat storage. Stritih *et al.* [11] presented the performance of a boiler with a built-in thermal storage unit. The thermal storage unit was an insulated water tank that absorbed surplus heat from the boiler. The stored heat in the thermal storage unit made it possible to heat even when the boiler was not operating, thus increasing the heating efficiency. The model of the system and the mathematical model were made using the TRNSYS program package and a test reference year. Verda *et al.* [12] presented a multi-scale model of storage tanks. This model was particularly suitable to analyze the operation of storage systems during the heating season and to predict their effects on the primary energy consumption and cash flows. The analysis was conducted considering the Turin district heating system as case study. Results showed that primary energy consumption could be reduced up to 12%, while total costs could be reduced up to 5%. Grahovac *et al.* [13] presented a simplified model of primary HVAC system with an on-off boiler, thermal storage and solar thermal collectors which were simulated in the hour resolution. The simulation yielded results to an optimization algorithm that sized the system. The results showed a good model performance and short-term simulation time. The amount of user input data was minimized to allow the optimal configuration of choice during early building design, but also to avoid the system oversize.

Description of biomass heating systems

A biomass heating system consists of a heating plant, a heat distribution system, and a biomass fuel supply operation. The system under discussion includes a biomass boiler, a heat storage unit and the building. When the boiler is in operation, the heat that is produced is used to heat the building and is accumulated in the heat storage unit. Alternatively, the heat may simply accumulate in the heat storage unit. When the boiler is not operating, the heat storage unit supplies the heat that is used to heat the buildings.

Biomass boiler

For the purpose of this research, biomass boiler with capacity of 600 kW is proposed. Boiler efficiency varies with boiler output, according to data provided by the manufacturer. The combustion process is controlled automatically by using two control parameters: water temperature within boiler and temperature of exhaust gases. In order to achieve primary energy savings (fuel), the boiler operates on nominal load every time it is in operation (for the purpose of this research). Biomass consumption can be determined from the following expression:

$$\dot{m}_f = \frac{P_{\mathrm{boiler}}}{\eta_{\mathrm{b}} NHV} \tag{1}$$

Building

The analysis of heat storage and biomass boiler operation is investigated for the building located in urban part of the City of Niš. Designed heating load of the building is 600 kW. The building is a five-story residential building with four dwellings per story. Outside masonry wall is insulated with polystyrene and has *U*-value of 0.8 W/m^{2}K. Currently, the building is connected to the local district heating network, and heating energy consumption and water temperatures are monitored. From the previous heating season, temperature and consumption profiles were derived for three typical days.

Heat storage

The boiler is modeled as an ideal energy source. In each time step during which the boiler is turned on, the boiler operates at full load, delivering the amount of energy equal to its design power multiplied with the duration of the time step. The energy generated by the boiler is fed to the heat storage, which is characterized by its volume and discharge rate. Heat storage volume, together with the basic differentiation between low and high temperature heating, defines the maximal storage capacity. The discharge rate defines which fraction of the maximum capacity can be delivered to the load within one time step (under the condition that more energy is currently stored). Apart from its role in system performance control, this value regards the physical limitations of the distribution system. Another idealization is neglecting the heat storage tank thermal loss to the environment.

Sizing of heat storage

The basic purpose of the heat storage is to cover energy requirements for a predefined period *t*, when the unit is out of operation. The heat which is accumulated in the heat storage depends on the nominal power of the boiler:

$$Q_{\text{st}} = P_{\text{boiler}} t \tag{2}$$

where Q_{st} is the accumulated heat energy, P_{boiler} – nominal power of boiler.

The net volume of the heat storage *V* [l] is:

$$V = \frac{Q_{\text{st}}}{c_{pw}\rho_w \Delta t_{\text{st}}} \tag{3}$$

where c_{pw} is the water specific heat, ρ_{w} – the water density, and $\Delta t_{\text{st}} = t_{\text{h}} - t_{\text{c}}$ – network differential temperature. Changes in accumulated heat energy are equal to:

$$\frac{\mathrm{d}Q_{\text{st}}}{\mathrm{d}t} = m_{\text{st}} c_w \frac{\mathrm{d}t_{\text{st}}}{\mathrm{d}t} \tag{4}$$

Constraints are introduced for heat storage: the energy content ($Q_{\text{st},\,t}$) at time *t* in storage equal to the sum of the energy content ($Q_{\text{st},\,t-1}$) of the $t-1$ and charge/discharge heat flow ($-E_{i,t}$), *i. e.*:

$$Q_{\text{st},t} = Q_{\text{st},t-1} - E_{i,t} \tag{5}$$

Second, the water temperature (t_{st}) in the storage must not exceed the permitted maximum temperature ($t_{t,\max}$), *i. e.*:

$$t_{\text{st},t} \le t_{t\,\max} \tag{6}$$

Third, the minimum water temperature in heat storage must be greater than the supply water temperature to consumers – DH network:

$$t_{\mathrm{st},t} \geq t_{h,t} \tag{7}$$

For reference days, it is assumed that the water temperature is 80 °C in heat storage at the beginning and end of the heating period. Following the boundary conditions, if the water temperature in heat storage is higher than $t_{\mathrm{h,t}}$ temperature, the boiler is turned off. When the water temperature in heat storage approaches the temperature of $t_{h,t}$, the boiler starts to operate. In this part, heat energy delivered by the boiler is used to cover the heat load demand, and the rest accumulates in heat storage. The boiler operates with a nominal capacity. When the water temperature in heat storage achieves a maximum value (90 ºC), the boiler is turned off.

For the analysis, the equation for calculating the volume of heat storage was adopted during 1, 2 and 3 hours (eq. 2). Based on the adopted nominal boiler capacity (600 kW), heat storage volumes of 25,714 l, 51,429 l, and 77,143 l were obtained.

Results and discussion

The system was modeled using the Microsoft Excel programming platform and the Visual Basic programming language. The simulation was carried out using heat storage tanks of different volumes (25,714 l, 51,429 l, and 77,143 l). The hourly heat requirements during the entire heating season (from October 15 to April 15), as well as the external temperature profiles, were made available by the plant operator. These data are relative to the total area of connected buildings of around 4,500 m^2. The temperature and the heat load profiles for three typical days are presented in fig. 1 and 2. Using the temperature data during the entire heating season, the corresponding heat loads were calculated and compared to the real data provided by the district heating network operator. These data are the basis for the study of possible effects of using storage tanks connected to the district heating system. Based on the ambient temperature and heat load, the supply and return water temperatures were calculated. The mass flow was assumed to be constant and equal to its nominal value.

When fuel pellets, with a net heating value of 18,000 kJ/kg, were to be used, in order to calculate primary energy savings, boiler efficiency should be provided by boiler manufacturer. For this analysis, the following values of boiler efficiency based on manufacturer’s data were selected: for nominal load, boiler efficiency is 90%; for 30% load the efficiency decreases to 80%. The above data correspond to the boiler operating regime of 90/70 °C. To determine the water temperature in heat storage during charging and discharging, the described model was used with some constraints. The water temperature in heat storage followed the outdoor temperature, *i. e.* the temperature requested by consumers.

Figures 3-5 show temperature profiles of heat storage, as well as the heating supply temperature for reference days. Figure 3 shows these profiles for February 8 of the current year, when the average outdoor temperature was –5.2 °C. For heat storage volume of 25,714 l (0.04 m^3/kW), the average boiler operation time was 2 hours, with app. 1 hour when the boiler was turned off. During the heating period (5 a. m. to 9 p. m.), the number of boiler on/off cycles was 5. For heat storage volume of 51,429 l (0.08 m^3/kW), the boiler operation time was increased to 4 hours, and the shut-down period was 2 hours, with the number of boiler on/off cycles of 2.5. For heat storage volume of 77,143 l (1.3 m^3/kW), on/off periods were 6 hours/4 hours, respectively, which yielded the number of on/off cycles of 1.5.

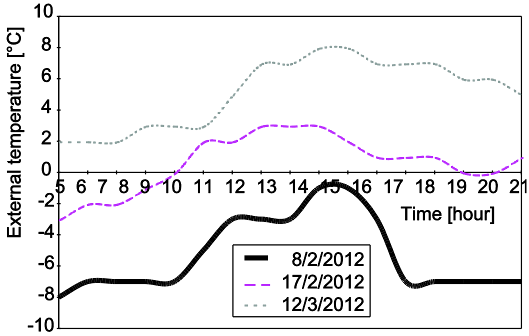

Figure. 1. External temperature variation with time of reference days

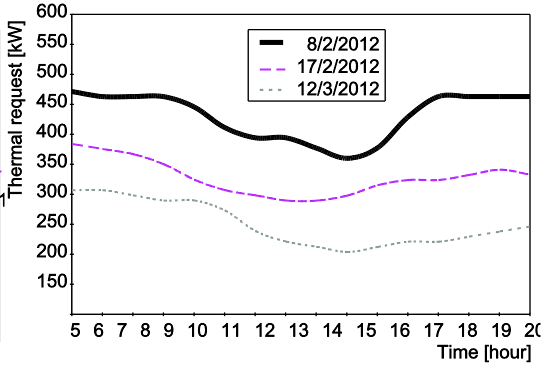

Figure 2. Thermal demand variation with time of reference days

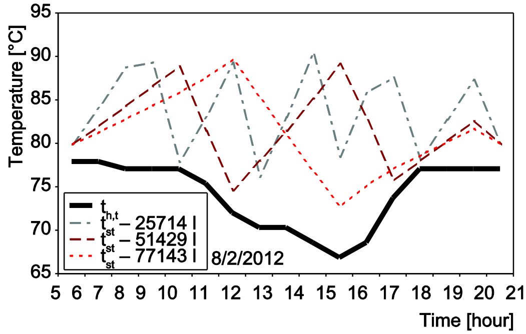

Figure 3. Profiles for water temperature in heat storage and supply water to consumers for 08/02/2012

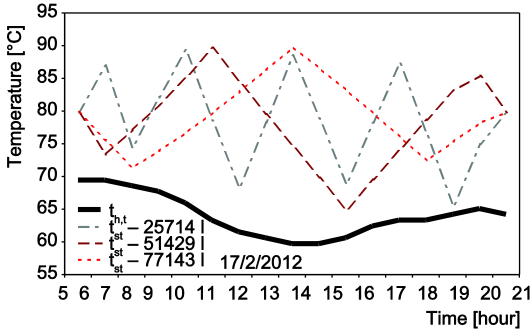

Figure 4. Profiles for water temperature in heat storage and supply water to consumers for 17/02/2012

For increased outdoor temperatures, the situation changed in the sense that the off period for the boiler increased. Figure 4 shows temperature profiles for February 17 of the current year, when average outdoor temperature was 0.65 °C. For heat storage volume of 0.04 m^3/kW, on and off periods for the boiler were 2 hours, and the number of boiler on/off cycles was 4. For increased heat storage volume of 0.08 m^3/kW, the duration of one on/off cycle was 9 hours, and there were 1.8 boiler on/off cycles in the heating period during the day. A significant increase of on/off cycle duration was observed for heat storage volume of 1.3 m^3/kW, which had the value of 11 hours (the boiler was on for 6 hours, and off for 5 hours). The total number of on/off cycles for the heating period during day was 1.4.

A similar analysis is presented in fig. 5 for March 12 of the current year when the average outdoor temperature was 5.2 °C. Due to significantly lower heating demand compared to the nominal one (app 35%), the periods during the day when the boiler was off were longer, and in the case of heat storage volume of 25,714 l, the number of on/off cycles was 3 (the boiler was on for 2 hours and off for 3.5 hours). The number of boiler on/off cycles decreased with the increase in heat storage volume. For heat storage volume of 51,249 l, this number was 1.6 (the boiler was on for 4 hours and off for 6 hours), and for the volume of 77,143 l, the number was 1.4 (the boiler was on for 7 hours and off for 4 hours).

From the analysis, taking into consideration the fact that the period between two boiler starts should not be too long in order to prevent boiler cooling, heat storage volume can be determined. For heat storage volume of 25,714 l, the number of boiler starts was higher, with shorter periods when the boiler was off. This difference is significant for case 3, so the volume of heat storage should be between 0.04 m^3/kW and 0.08 m^3/kW, which is in compliance with the results from other authors [11].

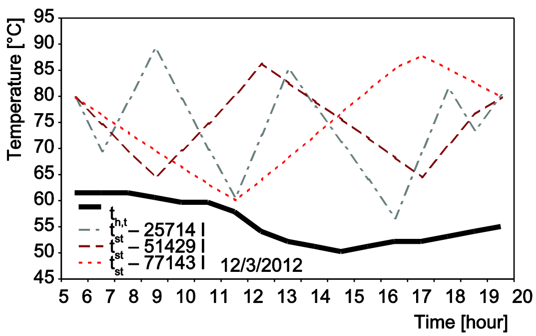

Figure 5. Profiles for water temperature in heat storage and supply water to consumers for 12/03/2012

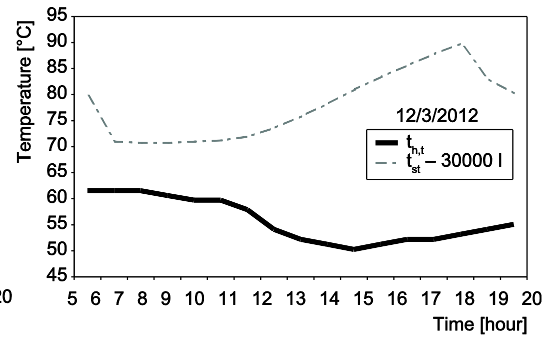

Figure 6. Profiles for water temperature in heat storage and supply water to consumers for 12/03/2012, working with two boilers

In the case of higher outdoor temperature, which is the case in 50% of heating season, the solution with 2 boilers is more acceptable. Only one boiler would be in operation, with short periods when the boiler is turned off. Figure 6 shows temperature profiles for heat storage volume of 0.05 m^3/kW for March 12 with two 300 kW boilers. The boiler was in operation for the larger part of the day. Besides covering the heating demand, heat storage was charged as well.

Since one of the assumptions was that the water temperature in heat storage remains the same at the end of the day compared to its beginning, heat storage volume does not influence fuel consumption. Adding heat storage to boiler plant decreases fuel consumption, due to the fact that the boiler operates all the time on nominal conditions, *i. e.* with maximum boiler efficiency. In tab. 1, fuel consumption is shown for all analyzed days for situations with and without installed heat storage (eq. 1). Primary energy savings are significant, and overall plant efficiency is increased. When the average outdoor temperature increases, primary energy savings increase as well.

Table 1. Fuel consumption and primary energy savings for reference days

Date	8/2/2012	17/2/2012	12/3/2012
Boiler operation time [hour]	11.5	8.8	7.75
Fuel consumption without HS [kg]	1,598.95	1,256.5	980.2
Fuel consumption with HS [kg]	1,533.33	1,173	900
Primary energy savings [%]	4.1	6.6	8.2

Conclusions

In this paper, the primary energy savings that may be achieved by using heat storage systems in district heating are discussed. One of the main problems with boilers is how to adapt their heating power when the heating system of a building does not need all the heat that is being produced. Building a heat storage unit into the heating system helps balance the boiler loads and improves the quality of the biomass burning. Heat from the boiler is stored in a heat storage unit, which then feeds heat to the building as required. The simulation shows that the heat storage volume must be optimized in such a way that all the heat of combustion can be stored at a sufficiently high temperature and that the time when the boiler is not working is short. With the change in heat load, shown for reference days, the time when the boiler is not working is changing, and it depends on the heat storage volume. The increasing heat storage volume reduces the number of cycles, and increases the period when the boiler is not working. Since it should be strived for less time for cooling of the boiler, it is necessary to choose the optimal value of the heat storage volume. The analysis shows that the heat storage volume should be in the range of 0.04 to 0.08 m^3/kW. During the period when the heat load is small, it is sometimes necessary to have two small boilers to reduce the time when the boiler is not working.

The installation of heat storage enables primary energy savings in the range of 4-8%. For higher average outdoor temperatures, the savings are greater.

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Nomenclature

c_{pw} – water specific heat, [$kJkg^{-1}K^{-1}$]
NHV – net heating value, [$kJkg^{-1}$]
P_{boiler} – nominal power of boiler, [kW]
Q_{st} – accumulated heat energy, [kJ]
$t_{h,t}$ – supply water temperature to consumers DH network, [°C]
t – time, [s]
t_{st} – water temperature in the storage, [°C]
V – net volume of the heat storage, [l]
Δt_{st} – network differential temperature, [°C]

Greek symbols

η_b – boiler efficiency, [–]
ρ_w – water density, [kgl^{-1}]

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