International Journal of Smart Grid and Clean Energy

Feasible microgeneration system for small amounts of solid biomass as fuel

Jorge Bedolla-Hernández, Marcos Bedolla-Hernández, Vicente Flores-Lara, José Michael Cruz-García, and Carlos Alberto Mora-Santos

Department of Metal-Mechanics, National Technological Institute of Mexico / Apizaco Institute of Technology, Av Tecnológico s/n, Apizaco, Tlaxcala, C.P. 90300, México.

Abstract

Solid biomass can be considered as an alternative to fossil fuels in microgeneration. Although there are currently options for biomass generation, these are mainly focused on continuous production, with the respective proportional amount of fuel consumption. In this study, the viability of applying a microgeneration system on a small scale is analyzed. The system uses solid biomass from forest residues as combustible. The size of the boiler in the system is similar to a domestic one with a capacity of 20 L. The study considers small amounts of solid biomass; therefore the arrangement of the initial configuration of the biomass in the fireplace is analyzed to achieve the best use of energy from combustion. The initial percentage of water contained in the boiler to reach a convenient relationship of steam and heating time of the system is analyzed. The amount of steam generated is small, and then the feed of steam to the turbine is variable in terms of mass flow and pressure; as well as its quality. For this reason, an adhesion turbine is integrated as part of the system to reduce the inconveniences in the operation of conventional turbines. The proposed system can operate in a range of up to 25000 rpm, depending on the variable mass flow. The results reveal that the microgeneration system can be regarded as a viable alternative to be applied in the microgeneration process.

Keywords: Adhesion turbine, microgeneration, small scale, solid biomass

1. Introduction

The global demand for energy is continuously increasing. Therefore, it is necessary to diversify the available energy sources to meet the growing demand [1]. In this regard, in recent years it has been identified that low-grade heat sources are gaining widespread attention for energy production [2]. It is based on advantages such as environmental impact mitigation and reduction in production costs [3]. In addition, low-grade heat sources are available in the surrounding environment such as waste heat and biomass [4]-[6]. Among the available options as energy sources, biomass represents ancient and recent proved applications for low-grade heat sources, which include since heating up to current applications focused on heat and power generation [7]. Biomass as renewable source of energy is the third largest source in the world [8] and its combustion represents a low level of emission of solid particles [9].

Solid biomass is a type of biomass that can be obtained from forestry and agricultural residues, and wild plants, as well as it does not require additional facilities for storage and transportation. The exploitation of these residues is highly important because otherwise they become garbage [10]. Cyclical operations in the agricultural process produce considerable amounts of solid biomass. Such is the case of fruit tree pruning cycle, whose activity produces woody biomass materials such as branches and trunks [11]. This biomass can become an essential source for the production of steam and power energy [12].

Woody biomass from forest residues is the biofuel with the lowest heat production cost compared to fuels such as fossil and even compared to biomass pellets and briquettes. Because woody biomasses

* Manuscript received November 17, 2020; revised March 23, 2021.
Corresponding author. *E-mail address*: jorge.bh@apizaco.tecnm.mx.
doi: 10.12720/sgce.10.4.270-277

requires less power for its preparation as fuel, do not require special facilities, and no pretreatments for its use in combustion processes are required [13], which represents economic and energy savings for microgeneration [14]. The woody biomass is a viable alternative both socially, economically, and environmentally as a fuel for its low costs of heat production, and applications focused on medium and small power [15]. However, the calorific value of this type of biomass is lower than other fuels with pre-treatment, but this limitation can be overcome with the other advantages that biomass presents. Therefore, the analysis of the application of woody solid biomass for small-scale boilers is a field of opportunity in technological proposals [16]. In this regard, [17] established that biomass can be used in combustion plants of all sizes, including stoves and small heaters for small-scale consumption.

In addition to the drawbacks of low calorific value for solid biomass, commercial solutions for systems below 10 kWe are virtually unavailable [18]. An alternative for the application of low grade heat sources in the generation process is represented by ORC (Organic Rankine Cycle) systems [19]. But the disadvantage of ORC is that they tend to be excessively expensive and dangerous, due to the high cost of manufacturing, and that the working fluids in ORC systems are not very friendly to the environment [20].

In small scale systems for the generation, besides not having commercial systems commonly for this purpose; in furthermore, commercial expanders are not designed to operate under highly changing conditions of the working fluid. Thus, the integration of the expander for a microgeneration system represents another challenge. An alternative that seems to overcome the problems in the expander due to the reduced and alternating amount of working fluid is the adhesion turbine [21]. This turbine has a good performance to operate at relatively low pressure ratios [19], low power range [22], and is capable of generating power for a variety of working media like Newtonian fluids, non-Newtonian fluids, mixed fluids, and particle-laden two-phase flows [23]. The structure of its rotor is based on flat discs, it make the adhesion turbine relatively inexpensive to manufacture, operation, and maintenance [24].

According to the previous statement, it is evident that the diversification of energy sources is required to cover the current growing demand. One part of these sources is represented by low grade heat sources, such as solid biomass from forest residues. The advantages of using solid biomass directly as fuel are diverse, and its applications have a main focus on small-scale generation applications. The literature review identified that it is not common commercial equipment available for reduced levels of generation. This opens up technological challenges for application at various scales, including micro-generation systems. Another challenge in this sense is the adaptation or design of turbines that may correspond to the conditions of low power and reduced amount of steam. Based on the above, this study proposes and analyzes a system focused on microgeneration, with reduced amounts of solid biomass. The system integrates a boiler that operates on direct flame from solid biomass as fuel. The adhesion turbine, with reduced size and low power, allows a wide variation in operating speeds, depending on the steam flow, as well as supports repeated stops and starts in the system.

2. Components of the Microgeneration System

The microgeneration scheme consists of generating steam in a boiler to drive a microturbine. Both the adhesion microturbine and the boiler are designed with reduced dimensions. The components of the system for small-scale power generation are focused on solid biomass as fuel, which corresponds to the forest woody residual. The heat energy resultant of the biomass combustion is in direct contact with the surfaces of the boiler.

2.1. The boiler

The boiler focuses on a small-scale generation, and then it has reduced dimensions. The size of the boiler is similar to home accessories, such as a stove or water heater. The boiler container is established with an external diameter of 40 cm, a chimney diameter of 20 cm, and a volume capacity of 20 L. The boiler operates by burning solid biomass obtained from forest woody residual. The size of biomass pieces is proportional to the boiler size, and then a manageable length for pieces of firewood is considered around 30 cm. The working pressure inside the cylindrical container is considered up to 600 kPa for the tests. A security valve for 650 kPa is part of the protection. The temperature in the boiler, for working pressure, is between 120 ℃ and 150 ℃. The values of temperature and pressure are related to the operation of the adhesion microturbine. The characteristics of the boiler are shown in Fig. 1.

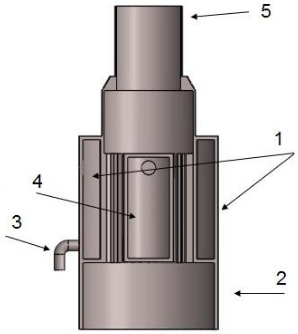


Fig. 1. Structure of the boiler, where: 1) water container, 2) combustion zone, 3) drain, 4) flame diffusor, 5) chimney.

2.2. The adhesion turbine

The turbine considered is an adhesion turbine, this concept is based on the mathematical model proposed by [25]. The selection of the model considers the fact that the quantified relationships are dimensionless; therefore, it provides a wide range of solutions because it is parametric. This model was coded in Matlab® and compared with the results of the literature [25]. The highest difference with that published data was 3.36% for the case of the maximum efficiency of the turbine.

Focusing on the concept of small-scale, the theoretical mechanical output power on the turbine shaft is 1 kW. Based on the temperature range from the combustion of solid biomass, the water steam is the working fluid. The operation of the boiler and turbine is established for the range of saturated water steam. Nominally, the system has a pressure of 300 kPa and temperature for the steam around 133.5 ℃. The pressure and temperature values are regarded to be typical of a boiler and are viable for steam generation with solid biomass. The use of steam is justified, since it does not require pretreatment to be used in the turbine, this contributes to the savings of costs. Then, a diameter of 213 mm was considered as the external diameter of the turbine, it corresponds to commercial tubes. Commercial components permit savings in the manufacturing process. The material is stainless steel due to it has very good adhesion energy with water. Then, from defining characteristics such as the power of the shaft, size of the casing, working fluid, and based on the model [25], the geometry of the disc was obtained. The characteristics of the adhesion turbine are shown in Table 1 and a representation is shown in Fig 2.

Table 1. Design values of the adhesion turbine

Characteristic	Value	Units
Outer radius, inner radius	106.5, 13.0	mm
Gap between discs, disc thickness	0.33, .892	mm
Torque	0.562	N·m
Mechanical power of design	1030	W
Discs	24	--

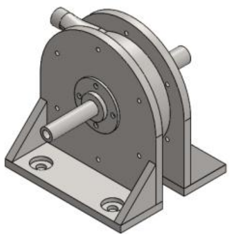


Fig. 2. Adhesion turbine.

2.3. The instrumentation

The monitoring of the boiler parameters focused on the pressure and temperature inside the container. For temperature measurement the thermometer is of the bimetallic DE-WIT® type with a range of 0 to 200 °C and an accuracy of ± 1%. The manometer is DE-WIT type, model 11, with a range of 21 kg / cm^2 and an accuracy of ± 2%. The monitoring of the steam mass flow was carried out with a Krohne flowmeter, model OPTISWIRL 407 vortex. The flowmeter measures the flow of liquids, gases and vapors, as well as the standard mass and volumetric flow rates of conductive and non-conductive fluids, even at fluctuating pressures and temperatures. This is accurate for steam flow conditions for a small boiler with a variable amount of steam. The turbine shaft speed is measured with a DT-6235B tachometer non-contact mode. The integrated system is shown in Fig. 3.

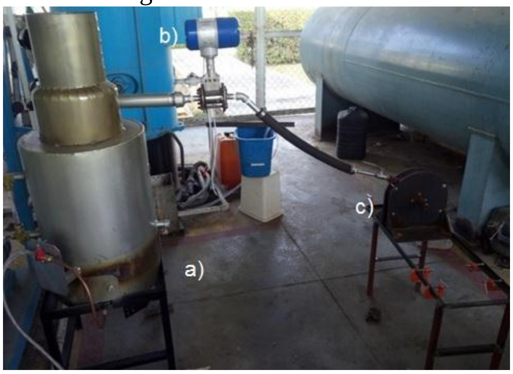


Fig. 3. System proposed for microgeneration, where: a) boiler, b) flowmeter, and c) adhesion turbine.

3. Methodology

3.1. The system

One of its goals is the reduction of fuel and energy consumption in general for the process. Under that concept, the system is considered to work in initial passive conditions, that is, it does not include engines or pumps. These considerations are based on the amount of biomass to generate steam and the amount of steam obtained. The system is initially with no additional energy consumption other than that of the biomass. Therefore, the initial independent variables of the passive system are the amount of biomass as fuel and the initial amount of water in the boiler container.

3.2. The initial arrangement of solid biomass

To establish the arrangement of the initial configuration of the biomass in the boiler house, are taken as a basis 2 L of water in the container. In that sense, the variations are made in the configuration that the biomass may have for a fixed amount, for this case 2 kg. The biomass is introduced into the combustion zone, where different arrangements are tested for the relative position of the initial biomass pieces before the combustion. The modifications of the arrangements include different average lengths and cross-sections of the pieces of woody biomass in each test. The variables analyzed in this test were the time of combustion, maximum temperature, and maximum pressure inside the boiler vessel.

3.3. Initial water quantity

These tests were carried out varying the initial volume of water in each of the tests. The volumes considered were 6 L, 8 L, 10 L, and 12 L (30% to 60% of the container capacity). Subsequently, the combustion is performed considering in all cases the same initial amount of biomass as fuel. The cut-off point of the test is to reach 550 kPa of pressure in the boiler. The definition of the initial configuration of the biomass arrangement and the initial amount of water in the boiler allows defining the combination of these parameters that maximize the operation for initial fixed amounts of water and fuel. From that definition, the initial point of opening of the working fluid to feed the turbine is obtained.

3.4. Electric generation

The pressure of 550 kPa inside the boiler is the starting point for feeding steam to the turbine. Due to the conditions of the system, this pressure value is instantaneous and decreases immediately when the steam flows to the turbine. As a consequence of this steam supply, the turbine gains speed. The quantity of steam and the speed of the turbine are related, and the speed is modified in proportion to the mass flow. The decrement in the steam flow to the turbine is consequence of the actual feeding, since the amount of steam in the boiler is reduced according to its dimensions. A commercial FRACTAL generator, model F40, is included for the electric generation process. The electrical quantities are affected by the speed that the turbine has in its operation. This is modified by the amount of steam flow that can be supplied.

4. Results and Discussion

4.1. Biomass arrangement

The relevance of determining dimensions and arrangement of the woody biomass used as fuel was analyzed. Woody biomass lengths between 12 cm and 25 cm were used, with different approximate diameters. The initial amount of water in the boiler was 2 L, and there was not steam flow for these tests. The first classification corresponds to whether the biomass has a grate arrangement of several layers or not. For tests 1 to 3 (see Fig. 4) the biomass did not have any arrangement. Tests 4 to 6 were carried out with a grate arrangement of biomass. For the remaining tests, in addition to the grate arrangement, a wire was used to hold that initial arrangement of the woody biomass together. For Fig. 4 "length” represents the average length of the biomass pieces, "diameter" is the average biomass diameter, "time" represents the duration of combustion, "pressure" is the maximum pressure in the test, and “temperature” is the maximum temperature. The Fig. 4 shows that the maximum temperature for all tests was similar; however, the maximum time and pressure show dependence on the type of arrangement and dimensions of the solid biomass. For the cases without initial arrangements (tests 1 to 3), the maximum pressure is lower than the rest of the tests, the same tendency is observed for “time”. The pressure and the time of combustion show a proportional relationship for all tests; where, the highest values are reached in tests 13 and 14. For this biomass arrangement, the woody pieces have average lengths of 20 cm and thickness of 10 cm. Then, a grate arrangement and holding the biomass together is the best initial configuration for combustion, and allows maximizing the time that the combustion lasts; as well as, obtaining the highest pressure inside the boiler. It is attributed to the fact that a grid arrangement allows air to be better distributed throughout the biomass grate and to circulate better from the bottom. Additionally, keeping the biomass together during combustion increases the combustion time and calorific energy.

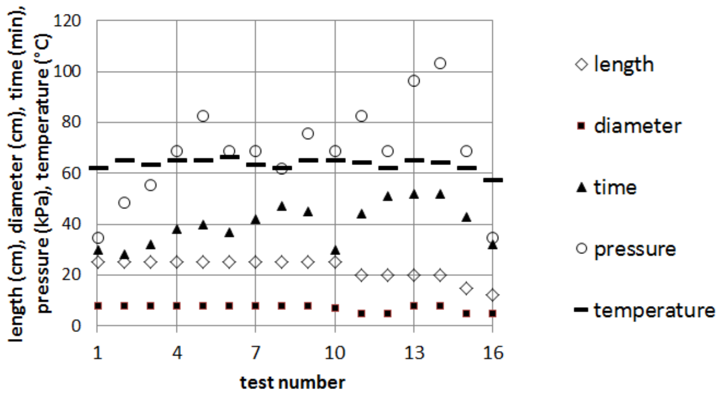
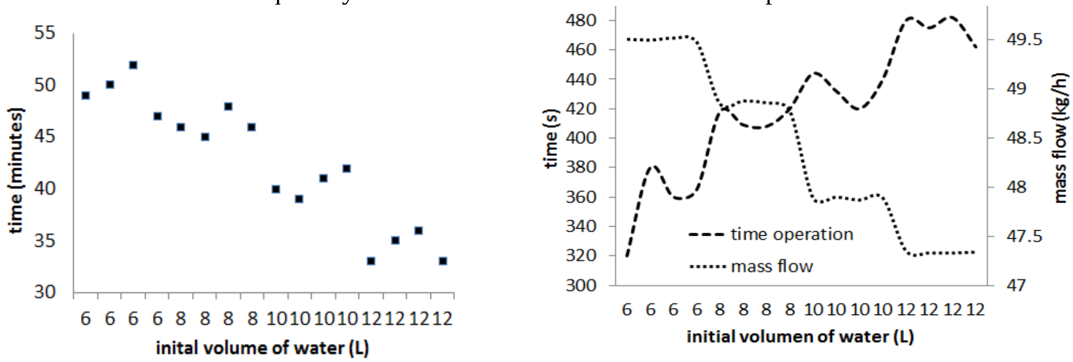


Fig. 4. Results for initial configurations of solid biomass.

4.2. The initial amount of water

The initial volume of water in the boiler was established by conducting tests at various initial volumes (6 L, 8 L, 10 L, or 12 L). Once the specified volume of water is introduced into the boiler the combustion is performed to generate steam, and the steam is feed to the adhesion turbine. This drives the turbine and, but as a consequence of the flow the pressure and the mass flow drop for a time up to the turbine stops. The parameters measured in these tests correspond to the initial volume of water, the time to reach the working pressure, the mass flow of steam, and the operating time of the turbine. Fig. 5a) shows the time required by the boiler, to reach the working pressure for different initial volumes of water. Fig. 5b) shows the operating time of the turbine and the mass flow for each initial volume of water. In Fig. 5 can be seen that with 12 L of water inside the boiler the pressure of 550 kPa is reached in short time, compared to 6 L, 8 L, and 10 L. However, with 12 L, the turbine has the shortest operating time; therefore, the volume of 10 L is selected as the initial quantity of water in the boiler to increase the operation time.



(a) (b)

Fig. 5. Time: (a) to reach the working pressure and (b) operation of the adhesion turbine and mass flow of steam.

4.3. Proposed generation scheme

Once established the initial parameters of the operating conditions on the generation scheme are carried out generation tests. The calorific value of the firewood is considered as 15909.84 kJ / kg. Once the feed of steam to the turbine starts, the mass flow value decreases. The decrement of mass flow arrives at a point where the turbine stops, for this point the feed valve is closed while the combustion continues until the pressure working is reached again inside the boiler. This cycle is repeated in the generation process. As a representative curve of the relationship between flow and velocity change as a function of time is shown in Fig. 6, this behavior is analogous for all cases.

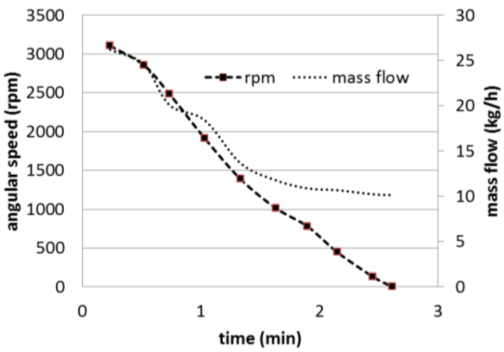


Fig. 6. Evolution for mass flow and turbine speed.

From the tests carried out just is obtained 26% of mechanical power considered in the design of the turbine. The mechanical power is related to the speed of the turbine and the torque, which depends on the mass flow, and the characteristics of the fluid. For voltage generation, the tests were carried out with and without electrical load on the generator. The load is a 12 volt 35 Ah battery, the Fig. 7 shows the voltage obtained from the generator as a function of the turbine revolutions. The curves corresponding to tests 1 to 10 were carried out without the electrical load, and the other tests were carried out with the battery as an electrical load. Fig. 7 shows that for the generator running without load presents an available voltage of 27.5 V to 1 V, for a turbine speed between 40 rpm and 580 rpm. When the generator operates with the load electrical, the turbine revolutions decrease to a range of 50 rpm to 250 rpm, consequently, the generated voltage is reduced at a level between 10 V to 1.5 V. However, Fig. 7 also allows estimating that for loads that require reduced current, the system is viable, and the generated voltage can increase within the range obtained for the generator. This allows concluding that the proposed scheme for microgeneration conditions is viable for small scale with biomass as fuel.

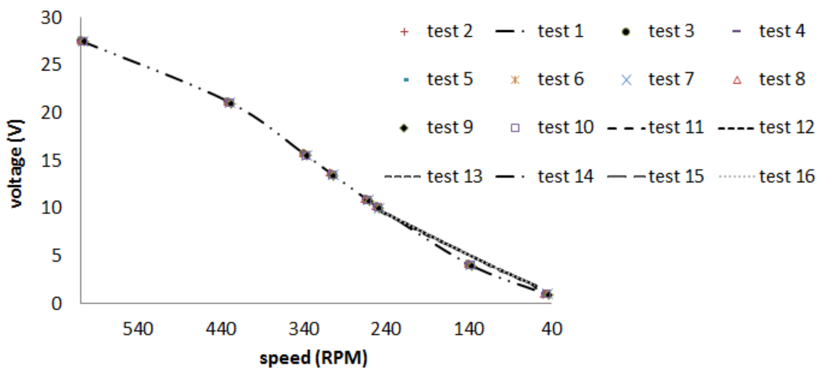


Fig. 7. Voltage generated.

5. Conclusion

The outstanding characteristics of the scheme proposed are based on its reduced dimensions, the consumption of biomass is reduced, it is an initially passive system, and the fuel is obtained from residual forest. The amount and initial arrangement of the biomass improves the combustion process. The woody biomass did not have any previous treatment, which reduces costs. An initial percentage of 50% water in the container reduces the combustion time for a suitable level of steam. The pressure, mass flow, and steam quality conditions modify the power of the turbine. But the microturbine proposed could operate for different: mass flows, speed revolutions, and loads. It can even have repeated stops without affectations. The electric power generation obtained is within the range of commercial batteries. In general, the proposed system is viable for small-scale applications with solid biomass as fuel.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

JBH performed the microturbine design reviews, prepared the instrumentation, and wrote the manuscript. MBH performed the turbine calculations and supervised the turbine assembly. VFL and CAMS developed the process for obtaining the steam and prepared the steam generation data. JMCG experimented with the system and prepared the graphs. All authors had approved the final version.

Acknowledgements

The authors are grateful for the financial support from the National Technological Institute of Mexico under Grant 7914.20-P.

References

[1] Karim MR, Nasera J. CFD modelling of combustion and associated emission of wet woody biomass in a 4MW moving grate boiler. *Fuel*. 2018; 222: 656-674.

[2] Song J, Gu C, Li X. Performance estimation of Tesla turbine applied in small scale Organic Rankine Cycle (ORC) system. *Applied Thermal Engineering*, 2017; 110: 318–326.

[3] Muhammad I, Muhammad U, Byung-Sik P, Dong-Hyun L Volumetric expanders for low grade heat and waste heat recovery applications. *Renewable and Sustainable Energy Reviews*, 2016; 57: 1090-1109.

[4] Lu Z. Operation performance study and numerical analysis of the multi-objective adsorption system driven by low-grade heat of solar energy and industrial waste heat, *Solar Energy*, 2020; 199: 575-584.

[5] Deligant M, Danel Q, BakirF. Performance assessment of a standard radial turbine as turbo expander for an adapted solar concentration ORC, *Energy Procedia*, 2017; 129: 1085–1092.

[6] Deligant M, Sauret E, Danel Q, Bakir F. Performance assessment of a standard radial turbine as turbo expander for an adapted solar concentration ORC, *Renewable Energy*, 2020; 147: 2833-2841.

[7] Halina K, Amit A, Krzysztof M, Krystian K, Shalvin S, Lukasz N. A transition of a domestic boiler from coal to biomass – Emissions from combustion of raw and torrefied Palm Kernel shells (PKS), *Fuel*,2020; 263: 116718.

[8] Bilgen S, Keles S, Sarikaya I, Kaygusuz K. A perspective for potential and technology of bioenergy in Turkey: present case and future view, *Renewable and Sustainable Energy Reviews*, 2015;. 48: 228-239.

[9] Konieczyński J, Komosiński B, Cieślik E, Konieczny T, Mathews B, Rachwał T, Rzońca G. Research into properties of dust from domestic central heating boiler fired with coal and solid biofuels, *Arc. of Environmental Protection*, 2017; 43(2): 20-27.

[10] Liu G, Larson ED, Williams RH, Kreutz TG, Guo X. Making Fischer—Tropsch fuels and electricity from coal and biomass: performance and cost analysis, *Energy Fuels*, 2011; 25(1): 415–437.

[11] Boschiero M, Cherubini F, Nati C, Zerbe S. Life cycle assessment of bioenergy production from orchards woody residues in Northern Italy, *Journal of Cleaner Production*, 2016; 112(4): 2569-2580.

[12] Brand MA, Jacinto RC. Apple pruning residues: potential for burning in boiler systems and pellet production, *Renewable Energy*, 2020; 152: 458-466.

[13] Bianchini A, Pellegrini M, Rossi J, Saccani C. Theoretical model and preliminary design of an innovative wet scrubber for the separation of fine particulate matter produced by biomass combustion in small size boilers, *Biomass Bioenergy*, 2018; 116: 60.

[14] Karim MR, Bhuiyan AA, Sarhan AA, Nasr J. CFD simulation of biomass thermal conversion under air/oxy-fuel conditions in a reciprocating grate boiler, *Renewable Energy*, 2020; 146: 1416-1428.

[15] Rybak-Wilusz E, Proszak-Miąsik D, Kuliński B. Management of Solid Biomass in Medium Power Boiler Plants, *Journal of Ecological Engineering*, 2020; 21(1): 105-111.

[16] Zhou A, Xu H, Tu Y, Zhao F, Zheng Z, Yang W. Numerical investigation of the effect of air supply and oxygen enrichment on the biomass combustion in the grate boiler, *Applied Thermal Engineering*, 2019; 156: 550-561.

[17] Las-Heras-Casas J, López-Ochoa LM, Paredes-Sánchez JP, López-González LM. Implementation of biomass boilers for heating and domestic hot water in multi-family buildings in Spain: Energy, environmental, and economic assessment, *Journal of Cleaner Production*, 2018; 176: 590-603.

[18] Kaczmarczyk T, Żywica G, Ihnatowicz E. Experimental study of a low-temperature micro-scale organic Rankine cycle system with the multi-stage radial-flow turbine for domestic applications, *Energy Conversion and Management*, 2019; 199: 111941.

[19] Talluri L, Fiaschi D, Neri G, Ciappi L. Design and optimization of a Tesla turbine for ORC applications, *Applied Energy*, 2018; 226; 300-319.

[20] Ling-Chin L, Bao H, Ma Z, Taylo W, Roskilly AP. *State-of-the-art technologies on low-grade heat recovery and utilization in industry*, In *Energy conversion: Current technologies and future trends*, United Kingdom, Al-Bahadly, Ed IntechOpen, 2018.

[21] Qi W, Deng Q, Jiang Y, Yuan Q, Feng Z. Disc thickness and spacing distance impacts on flow characteristics of multichannel Tesla turbines, *Energies*, 2018; 12(1): 44: 1-25.

[22] Ciappi L, Fiaschi D, Niknam PH, Talluri L. Computational investigation of the flow inside a Tesla turbine rotor. *Energy*, 2019; 173: 207-217.

[23] Guha A, Sengupta S. The fluid dynamics of the rotating flow in a Tesla disc turbine, *European Journal of Mechanics - B/Fluids*, 2013; 37: 112-123.

[24] Manfrida G, Talluri L, Fluid dynamics assessment of the Tesla turbine rotor. *Thermal Science*, 2019; 23(1): 1-10.

[25] Rice W. An analytical and experimental investigation of multiple-disk turbine. *ASME Journal of Engineering for Gas turbines and Power*, 1965; 87(1): 29–36.