# Innovative solutions in the energy sector

*Viktor* Lyubov[1*], and *Anatoly* Popov[1]

[1]Northern (Arctic) Federal University named after M.V. Lomonosov, 17, Severnaya Dvina emb., Arkhangelsk, 163002, Russia

**Abstract.** Combined heat and power plants (CHPPs) allow for significant savings in primary energy resources and a reduction in environmental pollution. Mostly it is carried out using steam turbines. However, in the eighties of the twentieth century, a new promising direction in the development of cogeneration appeared. These are plants operating on the organic Rankine cycle (ORC). An analysis of energy innovations abroad is required for the development and adaptation of this direction to Russian realities. Therefore, an analysis of the energy and environmental efficiency of high-moisture biofuels and biofuel mixtures with high ash content was carried out in boilers operating as part of a CHP using ORC technology and traditional steam turbine plants. Some recommendations for the innovative development of small and medium-scale power generation were proposed.

## 1 Introduction

Programs for the transfer of energy facilities to the use of renewable energy sources are being implemented in many European countries. One of these sources is woody biomass, the use of which in areas with high forest potential is a very relevant solution. The Russian Federation has huge reserves of timber. Therefore, in regions with a developed timber industry, it can be considered as a serious energy reserve [1-7]. In addition, the use of wood fuel in such regions allows solving many problems, such as the utilization of wood waste at the enterprises of the timber industry, obtaining cheaper energy, and reducing emissions of harmful substances into the atmosphere. Since the carbon dioxide released during the combustion of biofuels is reused in the process of biomass growth and does not disturb the natural balance of carbon dioxide in the earth's atmosphere.

Currently, there are ample opportunities for the energy use of wood waste, but there are many factors that affect the efficiency of the use of woody biomass. For example, the moisture content of wood fuel can vary quite widely [4-7]. High moisture reduces the efficiency of the combustion process, increases the volume and toxicity of flue gases, and leads to difficulties in using wood fuel in existing combustion devices. Also, the grain-size distribution of the fuel has a significant impact on the combustion efficiency. Deviations in particle sizes, both upward and downward from the optimal value, reduce the efficiency of the combustion device. In addition, the physicochemical and thermal properties of different types of woody biomass have some differences. Therefore, knowledge of the specific

* Corresponding author: v.lubov@narfu.ru

features of woody biomass allows for qualified development and implementation of measures for the economically and environmentally efficient operation of boilers.

Combined heat and power compared to separate generation allows for significant savings in primary energy resources and a reduction in environmental pollution. Mostly it is carried out using steam turbines. However, in the eighties of the twentieth century, a new promising direction in the development of cogeneration appeared [8-13]. These are plants operating on the organic Rankine cycle (ORC).

Recently, the use of ORC technology for cogeneration and the implementation of energy-saving projects in the Russian Federation are also gaining popularity. However, the development and adaptation of this direction to Russian realities requires an analysis of energy innovations abroad.

The ORC cogeneration process is like the thermodynamic cycle of a conventional steam turbine (Figure 1), but a high molecular weight organic substance is used as a working fluid to drive the turbine. Various working fluids make it possible to efficiently use low-temperature heat sources in a wide power range (from several kilowatts to 10 MW and more in one module). The optimal choice of the working fluid determines the efficiency of the ORC installation and its ability to use "low-temperature" heat sources for the combined heat and power. Silicone oil is commonly used as the working fluid in a biomass CHP plant (bio-CHP).

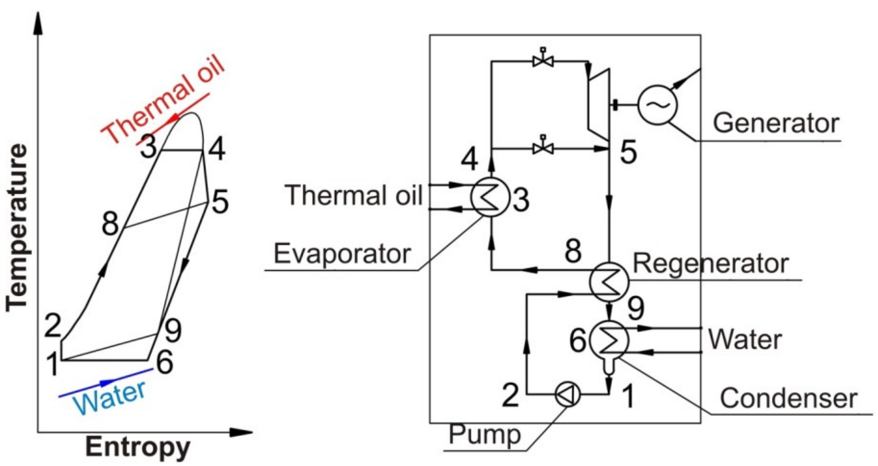



**Fig. 1.** Cogeneration based on thermodynamic regenerative ORC.

The vapors of the working high-molecular organic fluid formed in the evaporator do work during expansion in the turbine. The thermodynamic cycle is closed. In ORC-based plants, there are several independent circuits, while the heat source and coolant do not have direct contact with the working fluid or the turbine. In cases with high-temperature heat sources, such as bio-CHP, special thermal oil is used as a heat carrier, and an additional regenerator is installed to increase the efficiency of the thermodynamic cycle. Installations with such a technological cycle are usually called regenerative ORC. They usually have three independent circuits (Figure 1).

Compared to alternative technologies with the same electrical power, the ORC technology allows you to get the following advantages, confirmed by a survey of a CHP plant in the city of Bad Mergentheim (Germany):

- Higher overall cycle and turbine plant efficiency.
- Low mechanical stresses in the turbine due to low wheel speed.
- Absence of necessity for a gearbox between the turbine and generator.

- Elimination of drip erosion of turbine blades due to the lack of moisture in the working steam.
- Long service life without maintenance (up to 50 thousand hours).
- No complex water treatment system is required.

In addition, the long-term operation of plants with ORC has confirmed the presence of several operational advantages:

- Low noise level.
- Minimum maintenance requirements.
- Easy start and stop operations.
- Wide control range from 10% to rated power while maintaining good economic performance.

## 2 Materials and methods

The data obtained from the automated process control systems of the CHP were used to analyze and process the results of energy surveys. These systems provide automated control of the main parameters of the working fluids of all paths (fuel, steam, air, gas, etc.), as well as monitoring the concentration of solid particles and harmful gaseous components that are part of the flue gases emitted into the atmospheric air. The processing of the obtained results was carried out in accordance with the recommendations [14] and the innovations proposed in [4]. The calculation of emissions of harmful substances was carried out according to the methods presented in [15].

The thermal analysis of fuels and focal residues was carried out using the installations of the laboratory of complex thermal analysis. Fuel consumption was determined by the indirect heat balance equation.

## 3 Results

The bio-CHP plant in Bad Mergentheim is equipped with a thermal oil boiler (Fig. 2) with a thermal capacity of 5.15 MW, an electric generator from Turboden with an ORC module and two standby hot-water gas-tube boilers with a single capacity of 5 MW from BOSCH with burner devices for burning gaseous or liquid fuel. The electric capacity is 1.0 MW, and the thermal capacity is 14.1 MW, considering the standby boilers.

The furnace chamber of the thermal oil boiler is equipped with an air-cooled hydraulic grate. The project fuel is a mixture of bark, wood chips and logging waste. The boiler unit is designed for range of relative moisture of the biofuel mixture in the range of 30-60%, with a fuel ash content of up to 10%. The heat transfer fluid in the boiler unit is thermal oil, which imposes strict structural, technological and strength requirements for these boilers. Richard Kablitz GmbH, which has 122 years of experience in the power engineering industry, successfully coped with the solution of the increased requirements.

To ensure the most optimal distribution of primary air along the reciprocating grate, five zones are organized into which air is supplied after the air heater. Recirculation gases taken after the main exhauster are fed into the first three zones (Figure 2), which optimizes the process of thermal preparation of high-moisture wood fuel at the initial section of the grate. Biofuel combustion process on a reciprocating grate is carried out with an excess air coefficient of less than one, which creates prerequisites for reducing the formation of NOx. Additionally, recirculation gases are introduced through nozzles into the area above the fuel layer of the combustion chamber. The narrowing of the combustion chamber in the upper part allows mixing of flue gases, secondary air is blown in for afterburning combustible substances, which allows implementing a three-stage combustion scheme.

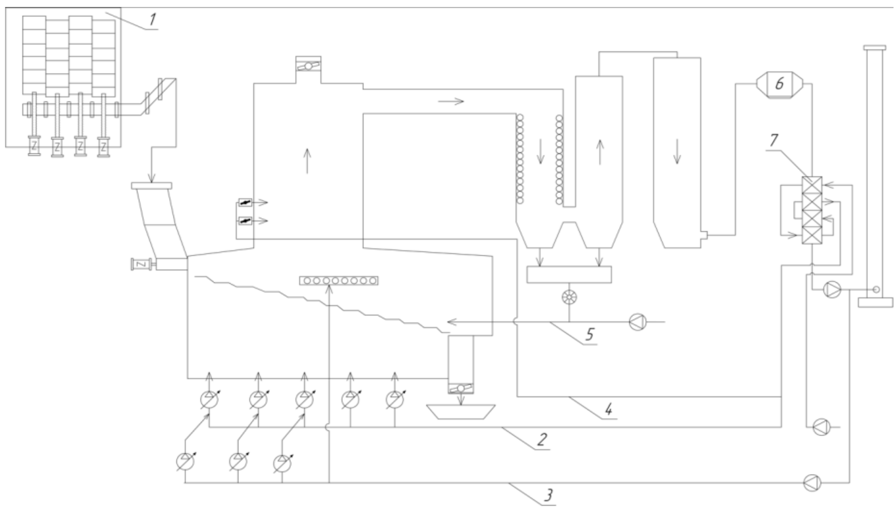



**Fig.2.** Technological scheme of thermal oil boiler unit of bio-CHP with ORC: 1– fuel storage with a moving bed; 2 – primary air supply; 3 – recirculation gas supply; 4 – secondary air supply; 5 – return of separated particles; 6 – electrofilter; 7 – recuperative air heater.

During the survey of the bio-CHP equipment with ORC, the gas temperature at the entrance to the radiation part of the boiler unit was 915-918 $^{o}$C (permissible up to 950 $^{o}$C), with a load of 6.10-6.17 MW. The average temperature of thermal oil at the boiler inlet was 118.4 $^{o}$C, and at the outlet 302.0 $^{o}$C. The oxygen concentration in the combustion products varied in the range of 6.3-7.3%, and the temperature of the exhaust gases was 146-154 $^{o}$C. The analysis of the components of the thermal balance of the boiler unit during the combustion of biofuels with the following thermal characteristics as received: moisture $W_t^r$ = 51.70; ash content $A^r$ = 0.82%; lower calorific value $Q_i^r$ = 7.844 MJ/kg, showed that its gross efficiency was 88.12-88.26%, and external heat loss 9.51-9.68%. The total biofuel consumption varied in the range of 3.161-3.202 t/h.

The rotation of the combustion products occurs when moving through the flues of the thermal oil boiler, which allows for partial separation of particles. The design of the Kablitz boiler plant provides for the return of separated particles to the fifth zone of the reciprocating grate, which ensures high completeness of combustion of substances in the focal residues.

Cleaning of combustion products at this CHP with ORC is carried out using an electrofilter, while the concentration of particulate matter in the removed combustion products was 0.5 mg/m$^3$ at an acceptable value of 10 mg/m$^3$. The high efficiency of the electrofilter ensured a very low level of particulate emission (0.4 mg/MJ). To reduce contamination of the heating surface of the air heater and increase its life cycle, it is located after the electrofilter (Figure 2). Its design implements a four-fold cross-current circuit, while the first input is made in the zone with the maximum temperature of gases, which eliminates the occurrence of low-temperature corrosion.

A modern system for monitoring the composition of combustion products ensures constant monitoring of not only the concentration of solid particles, but also carbon monoxide, nitrogen oxides and sulfur. During the survey of the boiler unit, the concentrations of these harmful substances were: CO = 10.0-30.0 mg/m$^3$ (permissible value up to 50 mg/m$^3$ with oxygen concentration of 11%), $NO_x$=123-143 mg/m$^3$ (permissible value up to 200 mg/m$^3$). Sulfur dioxide in the combustion products was practically absent due to the operation of the CHP on natural untreated wood. Analysis and processing of data from an automated stationary system for monitoring emissions for the specified range of boiler power changes, performed in accordance with [4, 14], showed that carbon monoxide emissions were 8.0-24.0; and nitrogen oxides 98.0-118.0 mg/MJ.

To compare the environmental indicators of various heat generating equipment, concentrations of toxic substances correct to an oxygen content: in Germany to 11%, in the Russian Federation to 6%, and in the USA and Great Britain to 3%.

For efficient combustion of high-moisture low-calorific biofuels, Richard Kablitz GmbH has developed, patented, and implemented "adiabatic" Kablitz Turbo-System combustion chambers, which allowed combining the advantages of layer combustion on a reciprocating grate and vortex combustion, which ensured minimal emissions of harmful substances.

Horizontal water-tube boilers have been developed and successfully used for burning biofuel mixtures with high ash content (wood waste, solid household waste, etc.). One of these boilers is installed at a thermal power plant in Wiesbaden (Germany). This CHP was installed and put into operation in 2013. The annual consumption of biofuels is about 90 thousand tons. The biofuel mixture is prepared in the process of sorting waste at a nearby plant.

A boiler unit of the "horizontal" type is installed at the CHP (Figure 3) producing superheated steam of an average pressure of 4.2 MPa with a temperature of 425 $^{o}$C. Its nominal steam capacity is 49 t/h at a feed water temperature of 130 $^{o}$C. A three-stage superheater with an in-line arrangement of coils is used to generate superheated steam. Provision of the standard temperature of superheated steam is carried out by means of two injecting steam coolers located between the stages of the steam heater. The high quality of the feed water preparation allows it to be used to regulate the steam temperature.

To ensure optimal distribution of primary air along the length of the reciprocating grate, six zones are organized into which primary air is supplied, while recirculation gases taken after the main exhauster are fed into the first four zones (Figure 3), which optimizes the process of thermal preparation of the biofuel mixture on the grate. The combustion process of biofuel on a grate is carried out with an excess air coefficient of less than one. Additionally, recirculation gases are introduced into the area above the fuel layer of the combustion chamber.

The flue gas cleaning system includes two installations, the first one is of inertial type (multicyclones), and the second one provides fine cleaning using bag filters. The gas treatment installations fully meet the stringent particulate emissions requirements.

The power of the steam turbine is 11 MW, it is equipped with an air condenser and provides the generation of 65000 MWh of electricity during the year. Thermal energy is used for district heating and amounts to 154000 MWh.

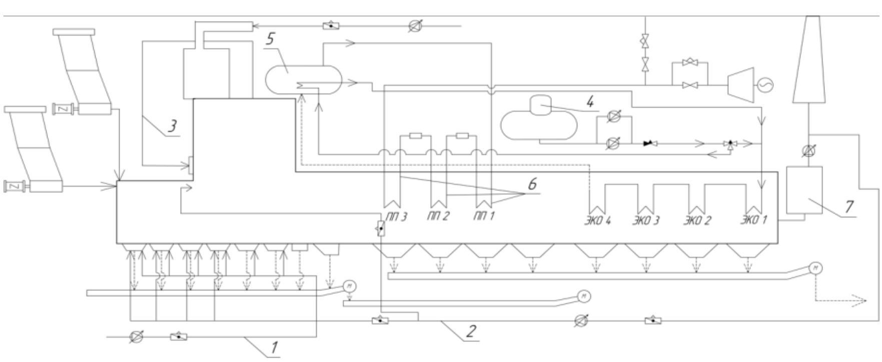



**Fig. 3.** Technological scheme of the bio-CHP boiler unit in Wiesbaden: 1– primary air supply; 2 – recirculation gas supply; 3 – secondary air supply; 4 – deaerator; 5 – drum; 6 – superheater stages; 7 – gas cleaning system consisting of a multicyclone and bag filters.

During the survey of the CHP plant equipment, the gas temperature at the inlet to the radiation part of the boiler unit was 921–954 °C at a load of 36.08–37.49 MW. The oxygen concentration in the combustion products varied in the range of 6.1–6.7%, and the flue gas temperature was 185–192°C. The high flue gas temperatures are because the boiler has operated for more than 7200 hours since the last cleaning. The analysis of the components of the thermal balance of the boiler unit during the combustion of biofuels with the following thermal characteristics as received: moisture $W_t^r$ = 39.03; ash content $A^r$ = 4.85%; lower calorific value $Q_i^r$ = 9.654 MJ/kg, showed that its gross efficiency was 86.52-86.64%, and external heat loss 10.90-11.04%. The total consumption of biofuel varied in the range of 15.491–16.115 t/h.

The fuel supply system provides for two-stage fuel purification from metal and other foreign inclusions, considering the heterogeneous nature of the combusted biomixture.

Vibration cleaning system ensures the removal of external crust from the heating surfaces. The operation of the boiler unit was characterized by a high completeness of burnout of combustible substances.

Modern automation and control systems provide constant monitoring of equipment operation parameters and composition of combustion products. During the survey of the boiler unit, the concentrations of harmful substances were: CO = 4.2-10.2 mg/m$^3$ (permissible value up to 50 mg/m$^3$), $NO_x$=84.5-96.5 mg/m$^3$ (permissible value up to 200 mg/m$^3$), $SO_2$ = 3.9–9.9 mg/m$^3$ (permissible value up to 200 mg/m$^3$ with oxygen concentration of 11%). As can be seen, the concentrations of harmful substances are much lower than the permissible values. The presence of a small amount of sulfur dioxide in the combustion products is explained by the content of municipal solid waste in the fuel mixture.

## 4 Discussion

When using of biofuel mixtures, which include municipal solid waste, wood waste, recycled wood, etc., a flue gas desulfurization unit is introduced into the technological scheme of the boiler unit, in which calcium hydroxide is injected, while the following reactions occur:

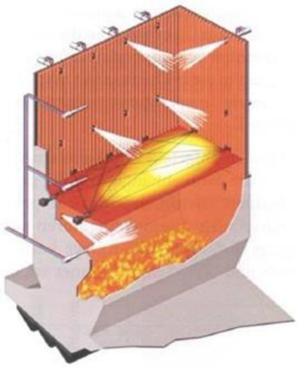
- $Ca(OH)_2+SO_2 \leftrightarrow CaSO_3+H_2O$.
- $Ca(OH)_2+SO_2+½O_2 \leftrightarrow CaSO_4+H_2O$.

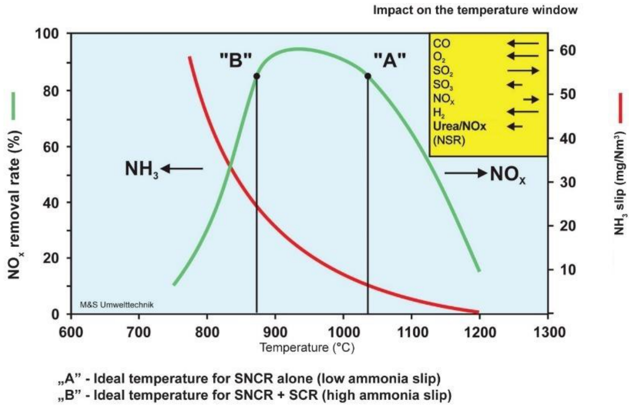
It should be considered that the mineral part of woody biomass contains a large amount of CaO (about 44%). Without the additional injection of calcium hydroxide, this allows for the binding of a significant part of the $SO_2$. During the energy survey, sulfur dioxide emissions had very low values of 3.0–7.0 mg/MJ. Emissions of other harmful substances were: carbon monoxide 2.0–5.0; and nitrogen oxides 71.0–79.0 mg/MJ.

When biofuel mixtures are burned, nitrogen oxides occupy a dominant position among the resulting harmful substances. Given this, all the necessary elements for equipping them with systems of selective non-catalytic (SNCR) (Fig. 4, a) or catalytic reduction (SCR) of nitrogen oxides are structurally considered. The efficiency of the first system is 60-90%, and the second is 94-98%. When using these systems, the following complex of chemical reactions proceeds (excluding side effects):

- $4NO+4NH_3+O_2 = 4N_2+6H_2O$.
- $2NO_2+4NH_3+O_2 = 3N_2+6H_2O$.
- $6NO+8NH_3+O_2 = 7N_2+12H_2O$.

When implementing systems for the reduction of nitrogen oxides, the injection of the reagent must be carried out in that zone of the gas path, where the temperature level ensures the maximum rate of reduction reactions (870–1040 °C). The maximum efficiency of purification of combustion products from nitrogen oxides is achieved using a combination of both SNCR and SCR methods.






(a) (b)

**Fig. 4.** The location of reagent injection devices in the SNCR system (a) and the optimal temperature range for the course of reduction reactions (b).

On heat generating units with a vibration cleaning system, retractable blowing devices are additionally used to ensure effective cleaning of heating surfaces when burning fuel mixtures with a high content of minerals. All the necessary holes in the enclosing structures of the equipment are provided and can be quickly used to install cleaning systems.

## 5 Conclusion

The general direction of the development of small-scale energy is the replacement of morally and physically obsolete boilers with new highly efficient automated heat generating installations of increased capacity with the predominant use of local fuels and waste from the timber industry, as well as the introduction of world-class innovative solutions for the creation of modern power plants for combined generation of heat and electricity using ORC technology.

The use of boilers equipped with reciprocating grate allows for the efficient use of local fuels and waste from the timber industry with a wide range of changes in thermal and granulometric characteristics. At the same time, high energy and environmental performance are ensured due to individual regulation of the movement of fuel in each zone as well as consumption of primary air and/or recirculation gases.

It should be borne in mind that the reciprocating grate, which affects the efficiency of fuel burnout and the life cycle of the boiler unit, is a very important and expensive element of boilers of small and medium capacity. Grates, which are partially or completely cooled by water, are used for burning fuels with high calorific value. Grates having combined cooling (air and water) are used when burning fuels with moderate calorific value, and when burning fuels with low calorific value – with air cooling. Combustion intensity of the grate surface with air cooling is 800 kW/m$^2$, and with water - 1000 kW/m$^2$.

To achieve a certain unification of the design of the furnace chamber, its walls should be made of water-cooled heating surfaces, and to achieve "adiabatic" conditions when burning high-moisture fuels, they are closed with refractory materials. The implementation of this technical policy makes it possible to significantly improve the parameters of starting and stopping boilers in comparison with boilers equipped with traditional "adiabatic" furnaces.

To achieve effective burnout of combustible fuel components and high environmental performance, the boiler unit should be designed with an average gas velocity in the combustion chamber not exceeding 5-7 m/s, and the residence time of flue gases at a temperature of 850 °C and above, which is at least 2 seconds. In potentially dangerous areas of high-temperature and chlorine corrosion, the heating surfaces should be covered with special pads. The low level of gas velocities significantly reduces the removal of ash particles and abrasive wear and contamination of heating surfaces.

The boiler units used must be equipped with efficient installations for cleaning the exhaust gases from solid particles. The type of gas cleaning installations and the number of cleaning stages used depend on the thermal characteristics of the fuel being burned and the current standards for particulate emissions.

Depending on the type and characteristics of the fuel being burned, boiler units should be equipped with cleaning systems for burner devices and work surfaces that ensure a minimum number of stops for cleaning them during the cold season. Considering the tendency of constant tightening of emission standards of harmful substances, all the necessary elements with systems of selective non-catalytic or catalytic reduction of nitrogen oxides and flue gas desulfurization installations should be constructively considered at newly introduced boilers. The design of the boiler unit should provide for the possibility of realizing the advantages of various combustion methods in one furnace device.

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