LOW GRADE HEAT RECOVERY SYSTEM FOR WOODFUEL COGENERATION PLANT USING WATER VAPOUR REGENERATION

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The paper analyses low grade heat recovery problem for modern woodfuel cogeneration plant. The woodfuel flue gas, behind the condensing economizer, still contains a considerable amount of heat, main part of which is the latent one. To recover this low grade heat, the heat pump technology can be used, which is related with additional consumption of energy (electric, mechanical or heat). Another technique that could be applied is a heat regeneration when flue gas heat, mostly latent, is transmitted to air blown towards burning chamber. Therefore, the analysed heat recovery system operates mainly like mass regenerator which contains only blowers that use some electric energy. The regenerator consists of two cyclically operating columns with packing material. Energetic analysis demonstrates that 13% of additional heat can be produced utilizing this low grade heat. The economic valuation shows that investment in a heat recovery system is quite effective; the payback time is about 4 years.

Key words*: cogeneration, woodfuel, heat recovery, efficiency, regenerator*

1. Introduction

Modern woodfuel cogeneration plants and heat only boilers are mostly fueled with freshly felled and chipped wood. Such fuel contains up to 60 % of water that reduces its calorific value and limits its usage for power plants of higher electrical efficiency. The problem could be partially solved by drying this fuel up to 30 %. This inevitably increases the fuel price and, consequently, reduces economic competitiveness. The competitiveness of these plants suffers also due to their relatively small capacity. The bigger the plant, the more efficient is its electricity production. By this parameter, woodfuel cogeneration plants concede to fossil fueled plants. The development experience of German biofuel cogeneration power plants states that their electric power should not exceed 20 MW because higher capacity plants require more fuel, the supply of which usually involves long distance transportation, while the decades of experience prove that the logistic radius of such plants is under 50 km [1].

Another important parameter of biofuel cogeneration power plants is their heat utilization efficiency which must be as high as possible. It should be even higher compared to fossil fueled plants because the low electricity generation efficiency must be compensated by a higher heat production efficiency. The utilization efficiency of modern woodfuel plants is quite high and may approach unity (i.e. 100 % based on *LHV*) due to the usage of economizers. However, even this value does not guarantee competitiveness of cogeneration power plants when the electricity is sold at the market price. Competition in a global electricity market is a big challenge for all cogeneration plants, therefore, seeking for higher efficiency is the way forward.

The recovery of low potential heat is important for all power and heat plants, not only for biofuel ones. Woodfuel flue gas still carries big amount of heat behind the condensing economizer, in particular when moist wood chips are fueled. Temperature of flue gas is too low to organize its heat transmission to the air blown for combustion. It is more rational to use heat pump technology for the utilization of this remaining heat [2, 3]. Both absorption and compression heat pumps are used for low temperature heat recovery. Both of them have advantages and disadvantages. For example, if electric power is produced inefficiently and the waste heat temperature is high enough (a case of *ORC* power plant, for example), it is rational to use technology of the absorption heat pumps. The generator of absorption heat pump requires heat source of 150℃ and higher. In case when waste heat temperature is of such high value, it is reasonable to use it in the absorption heat pump which produces almost twice of the used heat.

The absorption heat pumps and transformers are applied in different technologies of heat and electricity generation [4-8] including fuel cell technology [9] and refrigeration system [10] H. Lund et al., [11] note that waste heat of lower temperature could be utilized for space heating and, naturally, the heat pump technology should be used.

A number of articles that analyses economic and ecological advantages of compression heat pumps can be found in scientific literature [11-17]. Increased focus on heat pumps could be explained by heat *versus* electricity price balance which has slightly changed after the electricity market has been developed. Furthermore, a higher focus on heat pump technology is put because it is assigned, partially, to renewable energy technology, which is not still defined clearly. It should be noted, though, that R. Lowe [15] considers that cogeneration technology should also be classified as renewable.

Compression heat pumps are more suitable for the utilization of woodfuel waste heat because its temperature is relatively low behind the economizer. For example, if condensing economizer is used, the waste heat temperature is only 50℃, therefore this heat potential is not enough for absorption heat pump driving. However, the compression heat pump technology requires electrical or mechanical engine for turning a compressor and increases investment cost and energy consumption of the plant. The economic benefit of heat pump installation depends basically on the *COP* and on the price of the used energy. According to Lazzarin and Noro [14], compression heat pumps give more economic effect if electricity generation efficiency in the plant is higher, especially when the gas turbine combined cycle technology is used. As it has already been noted, the electrical efficiency of the woodfuel cogeneration plant is low, therefore the heat pump technology is not analyzed in this article.

This article presents a waste heat recovery system *(HRS)* and its analysis. Basically, the *HRS* is a mass transfer regenerator, where heat exchange takes place as well. Almost all latent and sensible heat is transferred to the air blown towards the combustion chamber. Air enters the fireplace with a much higher quantity of humidity increasing the concentration of water vapor in flue gas. As a consequence, higher humidity of flue gas increases heat capacity of the condensing economizer.

There is no information as regards application of this type of regenerators in heat and power plants. Jonsson and Yan [18] analyses humidified gas turbines. Air is charged by water vapor in mass transfer column, however, this is not heat regeneration and does not serve for low grade heat recovery. Water vapour regeneration is used in some heat regenerators related with ventilation and air conditioning where the usage of comparable expensive materials is economically reasonable [19, 20].

2. Heat-mass regeneration for waste heat recovery

The working principle of a heat-mass regenerator is similar to that of a heat-only regenerator. The both are storage-type exchangers whereby two fluids cyclically overflow their surfaces. There are two types of regenerators generally: rotary and fix-matrix. A rotary regenerator rotates, so its surface moves in turn towards one fluid and then towards another one. A matrix-fixed regenerator has a much larger surface and its mass. In this case both fluids are cyclically directed towards one or another column with packing. The flows of flue gases and air overflow cyclically two packed columns. Fresh air dries up and cools the packing of the first column and then, being warmer and of much higher humidity, is directed towards a combustion chamber. Meanwhile, the flue gas flows over the second column humidifying and warming its packing. After a certain period, the flows are reversed. The duration of the cycle depends on the heat capacity of the packing. The longer is the cycle duration, the lower are the cycling losses.

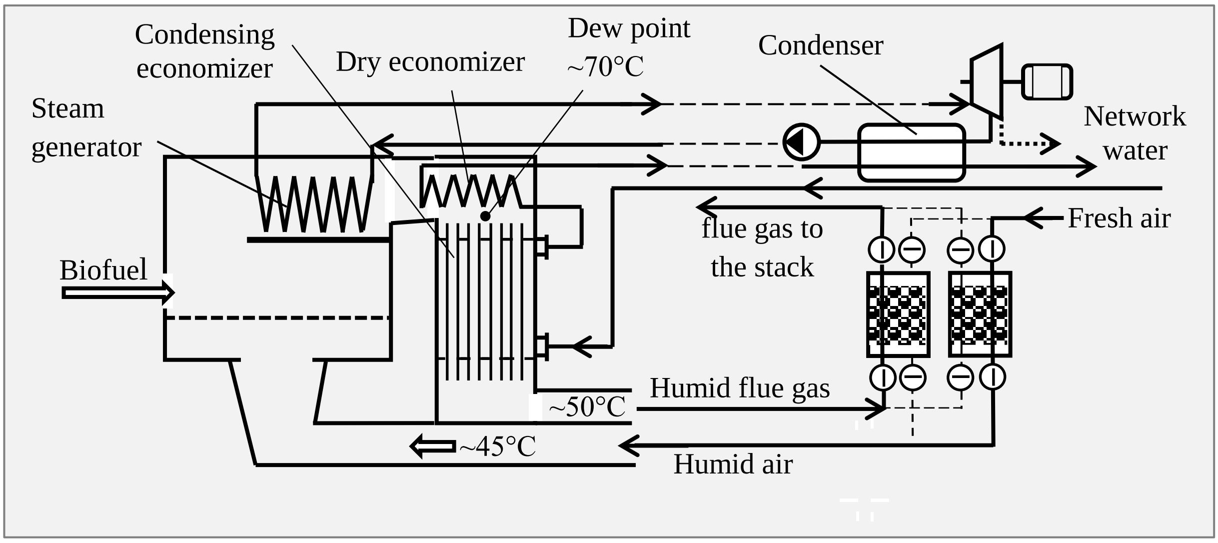

Fig.1. Scheme of biofuel cogeneration plant with latent heat regeneration

Another advantage of the *HRS* is related to the environmental requirement for flue gas cleanliness. Dust concentration is lowered when the *HRS* is used because small particles serve as starting centre of the condensation process and do not get into the surroundings.

Concerning other emissions such as nitrogen oxides NO_X and carbon monoxide CO, the situation is different. Due to a lower burning temperature, the NO_x concentration should be lower, whereas the CO – higher. According to Jonsson and Yan [18], the humid air does not deteriorate fuel combustion quality; consequently, it does not increase the CO emission.

The scheme of the cogeneration plant with the *HRS* is presented in the Fig. 1. The path of network water remains unchanged compare with the modern cogeneration plant with the economizers (plant with economizers could be called modern one). Meanwhile, heat capacity of the condensing economizer increases almost twice. The flue gas temperature after economizers is about 50 °C (Fig. 1). Usually, this flow leaves the plant through the stack (the stack is not shown in the Fig.1. Just between the stack and the condensing economizer, the mass and heat regenerator is placed. The fully humid (100 % of relative humidity) flue gas passes the regenerator and then gets into surroundings. Because of this, amount of heat that comes with flue gas into the condensing economizer is much higher. If the heat capacity of the condensing economizer is not sufficient, another like heat exchanger should be arranged. It could be better made of plastic fluorocarbon or of carbon steel coated with corrosion-resistant material (polypropylene, for example) [21, 26] to avoid corrosion problems which are sharper at lower flue gas temperatures.

3. Energy consumption of the wood flue gas

The working principle of a heat-mass regenerator is similar to that of a heat-only regenerator. The *HRS* does not change the electrical efficiency of the plant, however, additional amount of heat is produced by utilizing the flue gas heat behind the condensing economizer. This heat, mostly latent, is transmitted to air blown towards combustion chamber, so it comes back with a higher humidity of flue gas and is taken by the network water in the condensing economizer.

Additional amount of heat depends mainly on saturated concentration of vapor or its saturated temperature. As could be seen from the Fig. 2, air humidity increases exponentially with the temperature of the flue gas increasing. The saturated temperature or the dew point (pressure of gas does not change) of the flue gas depends on the woodfuel water content *(WWC)* and air excess ratio. For example, flue gas starts condensing at 62 ºC when *WWC* is 50 % and air excess ratio is 1.5 (Fig. 3) [2].

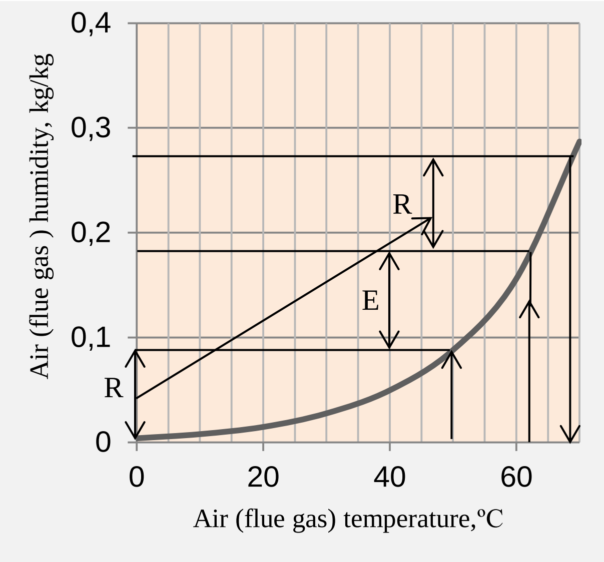

Figure 2. Comparison of recovered latent heat in condensing economizer and regenerator

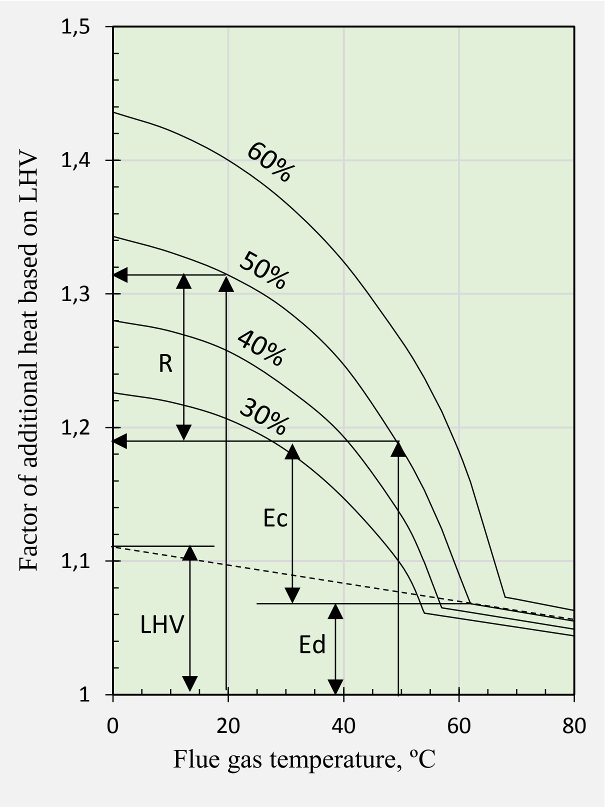

Figure 3. Relative heat increase of woodfuel flue gas subject to water content and temperature. Air excess ratio is 1.5, flue gas temperature behind boiler is 150 ºC, outside temperature is 0 ºC

Despite the fact that the temperature of the flue gas decreases insignificantly, nearly half of the water vapor turns into a liquid state (segment *E* in Fig. 2). Another part of the heat is normally released into surroundings (segments *R*). If this part of latent heat, together with the sensible one, is regenerated and is returned with air flow into the combustion chamber, condensation of water vapor starts at higher temperature, and more heat is received in condensing economizers (*E*+*R* in Fig. 2 and *Ed*+*Ec*+*R* in Fig.3).

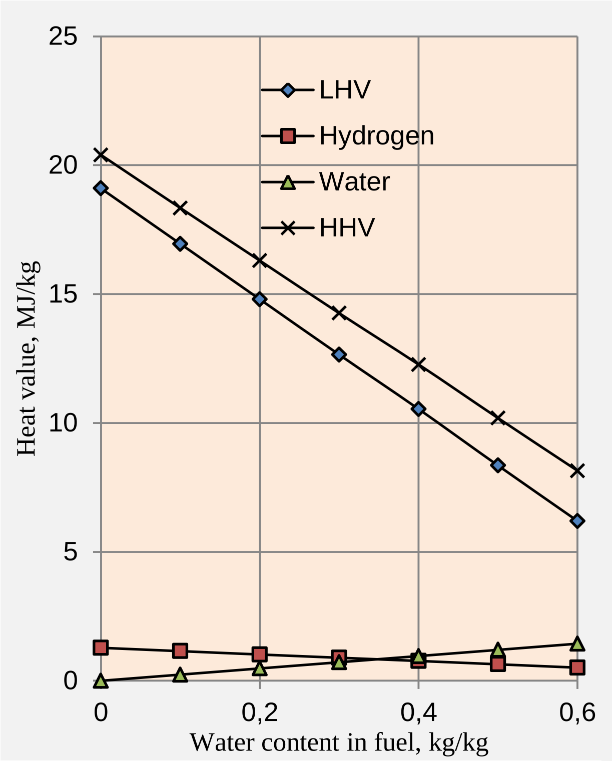

Figure 4. Wood fuel heating value

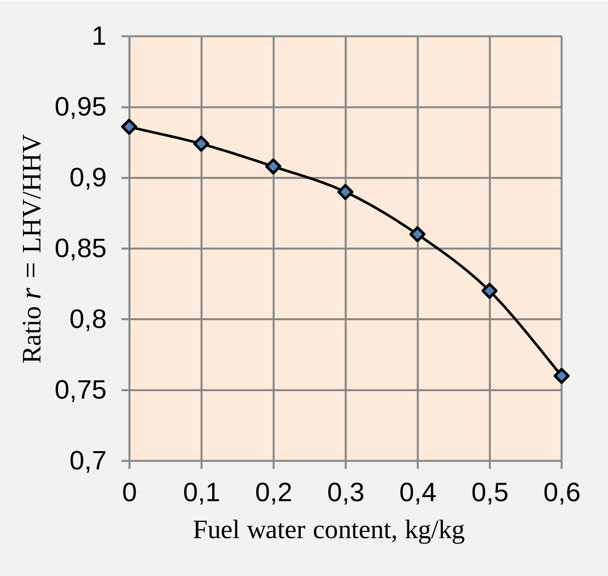

Figure 5. Ratio *LHV/HHV* subject WWC composition in accordance with water content

Usually, thermodynamic analysis of cogeneration plants is carried out when the lower heating value *(LHV)* of the fuel is valuated. However, in this particular case it is not convenient to do so, because a considerably part of the heat is produced by utilizing the latent one. The difference between the higher heating value *(HHV)* and the *LHV* of the woodfuel is considerable because of big amount water. The higher the *WWC*, the bigger is the difference between the *HHV* and the *LHV*. The *HHV* of fully dry wood differs from the *LHV* by only 4 %. Wood contains 5-7 % of hydrogen, which transforms into water vapor during the burning process. For the sake of calculation and analysis, the 6.2 % hydrogen value is accepted [21], so:

$$HHV^0 = LHV^0 + 20.6 \times \Delta H^0 = LHV^0 + 1.28 (MJ/kg) . \qquad (1)$$

The index ^{0} shows that the wood is fully dry; $\Delta H^0 = 0.062$ - the said hydrogen mass fraction in fully dry wood. It is evident that higher *WWC* value decreases the relational water vapour part from hydrogen and, naturally, increases the part of vapour from the *WWC* (Fig. 4). It can be seen that when approaching to 35 % of the *WWC*, both parts become equal.

The heating value of different types of woods differs slightly: the *LHV* of fully dry conifers is 19.2 MJ/kg, when that of the broadleaves is 19.0 MJ/kg. The heating value decreases directly to the water content growing. The relation between these values is [22]):

$$LHV = (HHV^0 - 20.6\times\Delta H^0)\times(1-\Delta W) - \Delta W \times h_{g-l} \quad . \qquad (2)$$

The ΔW is water mass fraction of the wood, $h_{g-l} -$ water latent heat, which is 2.40 MJ/kg at average 45 ºC. So the equation (2) can be simplified:

$$LHV = 19.1 - 21.5\Delta W \quad . \qquad (3)$$

The corresponding relationship for the *HHV* calculation is

$$HHV = HLV + 20.6\times\Delta H^0(1-\Delta W) + 2.40\times\Delta W \qquad (4)$$

If the HHV^0 value is known, the $HHV = HHV^0(1-\Delta W)$. The graphical relation r = *HHV/LHV* versus *WWC* is presented in Fig. 5.

An important parameter of the woodfuel flue gas is its dew point temperature or an initial temperature of vapour condensation during the gas cooling process. The higher the said temperature, the bigger amount of latent heat can be utilized. Moreover, the vapor condensation significantly increases the heat transfer coefficient from flue gas side. The dew point temperature depends on a partial vapor pressure, which can be determined when the vapor concentration is known. If the mass concentration is ω (kg/kg), the partial pressure can be calculated according to the equation:

$$p = \omega P_0 / (\omega + 0.622)^{-1} \qquad 5)$$

The initial condensation or the dew point temperature can be calculated:

$$t = 243.5\times\ln(p/6.112)/[(17.67 - \ln(\mathrm{p}/6.112)]^{-1} \qquad (6)$$

In these equations, the P_0 and p is atmospheric and partial vapor pressure in mbar, t – temperature in ºC.

From the equation (6), partial pressure can be expressed and then, using the (5), water vapor concentration ω can be calculated in case when initial temperature of condensation is known. For example, at the dew point of 62 ºC, the partial vapor pressure is p=221 mbar and concentration is ω =0.177 kg/kg. Using (5,6) equations, it can be estimated that the *HRS* increases the partial pressure p from 221 mbar to 296 mbar. The initial temperature of vapor condensation of the new composition of flue gas is 68.6 ºC, which is proven in Fig. 2.

4. Plant energetic analysis

Electrical efficiency of small and medium woodfuel cogeneration plant η_T is about 0.2 [1, 24]. The efficiency is not high because of low thermodynamic efficiency of the cycle when freshly felled and chipped wood is fueled. Additionally, it suffers because of relatively high losses of mechanical and electrical conversion (efficiencies η_m and η_{el} are nearly 0,95) and also of additional heat consumption l_{wn} for production of electricity required for own needs, which amounts to about 5 % of all electricity produced [1]. Therefore, the l_{wn} amounts 0.01 of the heat input because η_T is 0.2 based on the LHV.

Usually, the electrical (thermodynamic) efficiency of the plant η_T is known, so the input heat can be easily calculated. The amount of heat, produced by cogeneration plant, depends on various losses and possibility of their utilization. The mechanical and electrical conversion losses can hardly be utilized. The same is with the so-called burning losses, which includes losses due to incomplete combustion, heat radiation from the burning chamber, losses related with ash removing, etc. The burning losses l_b of a woodfuel plant make 2-5 % of the overall heat input *(LHV).*

Stack losses l_{st} make the main part of heat losses. These losses depend on the temperature of flue gas that leaves the plant through the stack. As can be seen from the case, analyzed and graphically presented in Fig. 3, stack losses amount 11 % of the input heat when the temperature of flue gas, entering the stack, is 150 °C (section LHV, Fig. 5). When economizers are used, the flue gas temperature is decreased to 50 °C and 19 % of additional heat *(Ed+Ec)* is recovered if the wood *WWC* is 50 %, for example. One could think that the heat utilization efficiency of the plant oversteps unity, however, this is because a considerable part of latent heat is recovered by condensing economizer.

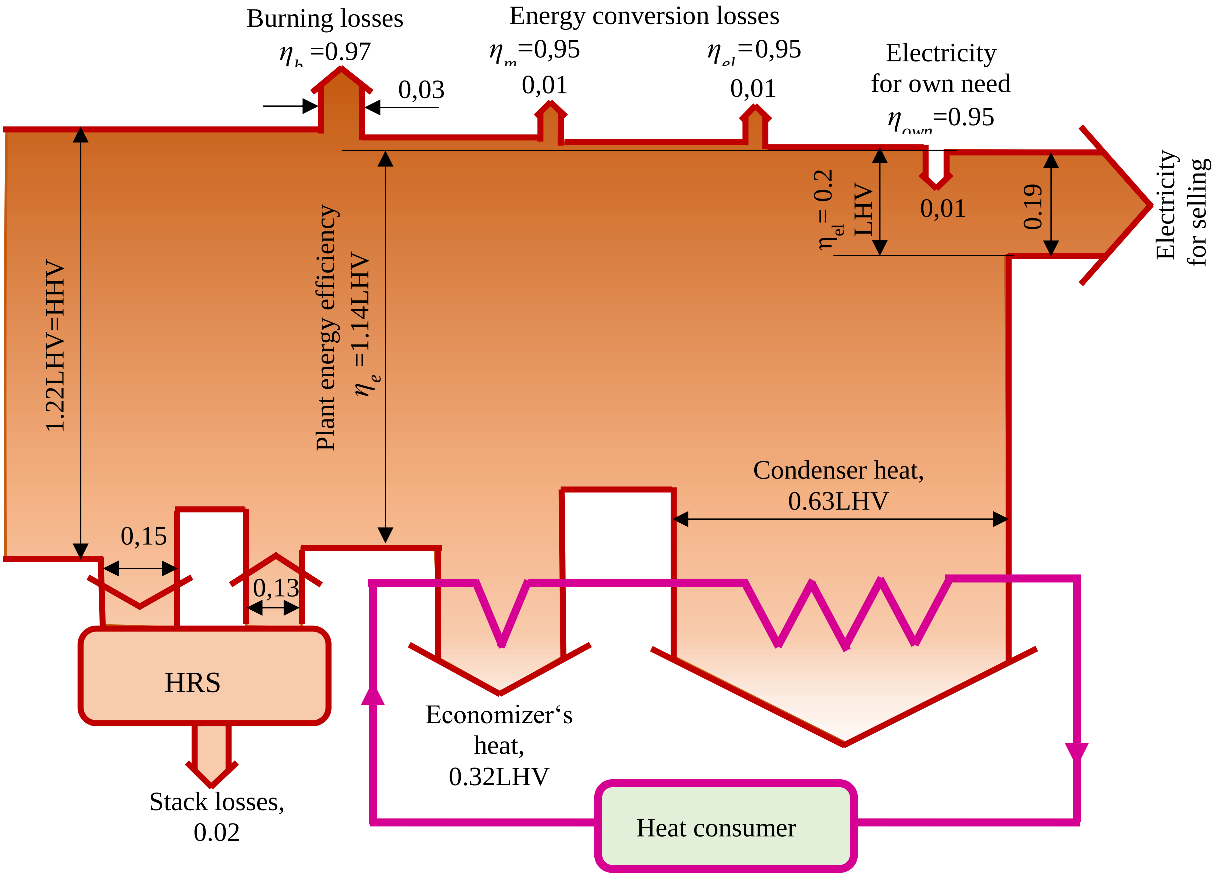

Figure 6. The scheme of energetic analysis for woodfuel cogeneration plant with heat recovery system Woodfuel water content is 50 %, air excess ratio – 1.5, temperature beyond boiler is 150 °C, efficiency η_T = 0.20

Stack losses can be reduced despite the fact that the flue gas temperature after condensing economizer is relatively low. If the *HRS,* presented in this article, is applied, stack losses could be decreased up to 2 %, as can be seen from Fig. 6. The HRS additionally recovers 13 % of the input heat in case the temperature of flue gas is reduced to 20 °C. This percentage can be estimated from the Fig.3: the section *R* makes 0.13. All recovered heat, due to the *HRS* appliance, amounts 32 % *(R+Ec+Ed=1.32).* According to the Fig. 3, the factor of all additional heat is 1.34, thus 34 % of the heat input can be recovered, if temperature of flue gas is reduced up to 0 °C, i.e. to the accepted mean temperature of the heating season. So the difference of 2% is the stack losses, which, together with the burning losses (average 3 %), energy (mechanical and electrical) conversion losses (2 %) and the losses related to the electricity consumption for own needs (1 %) make 8 % of the overall input heat Q_{in} .

The plant's input heat, in case when the latent heat is included, makes higher value, i.e. $1.22Q_{in}$. The quantity 1.22 can be calculated using the graphical relationship from the Fig.5. For example, ratio r is 0.82 for wood fuel with 50 % of the WWC, therefore all the input heat, including the latent one, oversteps the Q_{in} by factor $1/r$=1.22.

The scheme of energetic analysis of the woodfuel cogeneration plant (Fig. 6) is made on the basis of the LHV, but the latent heat of fuel is evaluated as well. All constituents of the energy produced, as well as various losses, are calculated on the basis of the *LHV*, therefore their sum makes 1.22. The comparative heat q_{out} , that the plant produces, can be calculated by the following equation:

$$q_{out} = \frac{1}{r} - \eta_T - \{1 - (1 - l_b)[1 - \eta_T(1 - \eta_m)] \times [1 - \eta_T(1 - \eta_{el})](1 - l_{wn})\} - l_{st} \quad . \tag{7}$$

The q_{out} can also be evaluated, but with a lower precision, from the scheme presented in Fig. 6.

For the cogeneration plant, which generates P_{el} of electricity power (MW), the heat input capacity in MW is

$$Q_{in} = P_{el} / \eta_T \tag{8}$$

Consequently, the heat capacity that plant produces is

$$Q_{out} = Q_{in} \times q_{in} \tag{9}$$

Overall energy efficiency of the cogeneration plant ηe is 1.14 (Fig. 6). For a more precise estimation, the equation $\eta_e = q_{out} + \eta_T$ can be used, where q_{out} is calculated by (7).

5. Economic evaluation of the HRS

The aim of the economic analysis is to show the economic attractiveness of investing into a novel *HRS*. Additional income is generated due to a higher capacity of produced heat. Additional expense is evaluated in view of a higher financial value of the plant and additional costs for operation and maintenance. Total investments are estimated by the cost calculation of several stages, such as [23]:

- bare erected cost (*BEC)*: on-site infrastructure, process equipment and material, initial labour for construction and installation;
- total cost of project (*TPC)*: comprises the *BEC* plus engineering, procurement, construction costs;
- total overnight cost (*TOC*): comprises the *TPC* plus owner's costs (environmental analysis and permission, preproduction, insurance, other owner's costs);
- total-as-spent cost *(TASC):* the *TOC* plus escalation during capital expenditure period (interest and escalation during construction).

The additional condensing economizer is the most expensive element of the *HRS*. As the flue gas from woodfuel contains corrosive products (sulphate, sulphite, chloride, nitric oxides), the material used for economizer's production must be corrosion-resistant. Stainless steel is a good choice, however, it is the most expensive compared to plastic or carbon steel coated with polypropylene. It is possible to calculate the price of the economizer according to Shen et al. [26]. The cost of the economizer of 3.9 MW (Table 1) would be 0.775 M€ when it is made from stainless steel.

Other investment cost of the *HRS* is relatively small due to inexpensive devices (the main of them are air blowers) and a simple construction – two 200 m^3 rectangular columns. The total amount of 600 tons of cobblestones ensures a sufficient heat inertia for normal cyclical operation with about 1 % of heat losses due to the cycling. At the same time, the packing material of each column ensures a surface of over 3000 m^2 for mass and heat transfer. The price of cobblestones (60-150 mm size) is assumed as 50 €/tone.

The stack price is accepted higher than proposed in Sayyaadai and Mehrabipour model [25] (3 US$/kg), because an additional cost of stainless steel is valued. It is assumed that the available territory of the cogeneration plant is sufficient for the *HRS* so there are no additional expenses for the land acquisition. The *BEC* composition of the *HRS* is given in Table 1.

Table 1. Composition of the BEC

ITEM	**COST,€**
Economizer (stainless steel)	775000
Other costs of the HRS	
Concrete	4200
Armature	3300
Steel timber	1300
Sheet (stainless steel)	7900
Heat insulation	2400
Cobblestones	30000
Blowers (4 units)and accessories	45000
Stacks	12000
Project, on-site infrastructure	8000
Unexpected and other materials	10000
All BEC cost, €	899610

Table 2. Capital cost of HRS

Capital costs	**M€**
BEC	0.8996
TPC(BEC × 1.6)	1.439
TOC(TPC × 1.04)	1.497
TASK(TOC × 1.08)	1.617
Cost before start-up	1.617

The total cost of the project (*TPC*) increases due to the costs related to engineering and construction processes as well as to the installation and start-up operations. For the initial valuation, these specific costs could be assumed as part of the *BEC*. Burer et al., [15] propose 60 % of the *BEC* for new innovative projects, therefore the *TPC* is 1.439 M€ (Table 2). The total overnight cost *TOC* is usually calculated as part of the *TPC*. Sometimes these expenses are not considered because they are not high. For example, for the combined heat and power plants the said part makes 3-5 % [23]. For the *HRS* case, 4 % of the *TPC* is taken (Table 2). The ratio *TASK/TOC* depends on the construction period and the financing scenario. In case the period is under 3 years and with a high investor-owned utility, this ratio is 1,078 [23]. It is assumed that the *HRS* construction and start up time is about 12 months, so a single interest rate of 8 % is taken for the borrowed capital. Thus, the capital costs before the start-up of the modernized woodfuel cogeneration plant is 1.617 M€ (Table 2).

The payback time is calculated by dividing the investment costs by the annual profit from the additional heat production, after having evaluated loan expanses (0.103 M€), additional fixed expenses (0.011 M€) and the decreased sales of electricity (by 0.532 M€/year, which is needed for the blowers of the *HRS*, Table 3). Total revenue during the accepted 25 years of lifetime of the *HRS* is 10.4 M€ and should amount about one third of the new like plant. All results of the economic evaluation are presented in the Table 3.

Obviously, the payback will be much shorter if the carbon steel with polypropylene [26] for economizer producing is used, or if it is made from polypropylene only [21]. Moreover, the plant economics should be more attractive if the decreased costs of heat production would allow compete other heat producers during non-heating season increasing the heat production capacity.

Table 3. Results of energetic and economic analysis of the woodfuel cogeneration plant: with and without the HRS

Parameters of the cogeneration plant	With HRS		Without HRS
	Case 1	Case 2	
Net electric power, MW (electrical efficiency $\eta_T = 0.20$ on LHV)[1]	6	5.18	6
Heat power input based on LHV Q_{in}, MW	30	25.9	30
Comparative heat q_{out} based on LHV, W/W	0.94	0.94	0.81
Energy efficiency of the plant η_e based on LHV	1.14	1.14	1.01
Heat power for selling Q_{out}, MW	28.2	24.3	24.3
Duration of heating season (capacity factor is 1.0), hours per year[2]	4320	4320	4320
Duration of non-heating season (capacity factor is 0.85), hours/year	3779	3779	3779
Part of Q_{out} that is pursued in non-heating season, %	20	20	20
Amount of electricity produced for selling per year, MWh [3]	47990	41431	48595
Amount of heat produced per year, MWh	143138	123342	123342
Amount of heat input per year, MWh	225965	195083	225965
Selling price of green electricity, €/MWh$_{el}$ [4]	51	51	51
Selling price of heat, €/MWh [5]	29	29	29
Woodfuel price, €/MWh [5]	11.1	11.1	11.1
Income from electricity selling, M€/year	2.447	2.113	2.478
Income from heat selling, M€/year	4.151	3.577	3.577
Expense for woodfuel, M€/year	2.508	2.165	2.508
Total investment in HRS, M€	1.617	1.617	-
Additional expenses for HRS, M€/year	0.065	0.011	-
Loan expenses during 4.2 years payback period, M€/year	0.103	-[5]	-
Annual revenue during the successive years, M€/year	0.375	- [5]	0
Payback time, years	4.3	-[5]	-
Total revenue during 25 years of operation, M€	10.4	- [5]	0

[1] – electric efficiency in both seasons is equal; [2] heating season is 180 days per year; [3] electricity consumption for HRS blowers decreases amount of electricity; [4] from the: http://www.regula.lt/siluma/Puslapiai/kuro-ir-perkamos-silumos-kainos/vidutine-salies-kuro-zaliavos-kaina.aspx ; [5] this case is not valuated because there is no possibility to sell surplus of heat.

6. Conclusions

Wood fueled cogeneration is one of the essential trends of modern renewable energy development. It complies with environmental requirements and is in line with national objectives of creating an independent energy source. Modern woodfuel cogeneration plants are not effective in power production, however they have reserves to increase low grade heat utilization despite the fact that a condensing economizer is used and part of the latent heat is utilized. To achieve higher heat utilization, a mass transfer regenerator can be proposed. Moisture from flue gas is transmitted to air which is blown towards a combustion chamber. Humidified air ensures a higher moisture concentration in flue gas and leads to an increase of recovered heat in the condensing economizer.

The heat recovery system *HRS* with a fixed-matrix regenerator is introduced as well as energetic and economic analysis is presented in the article. Two fluids, air and flue gas, flow cyclically over the packing in the columns. A big mass of packing material of the *HRS* regenerator conditions lower losses of cycling. This also provides a large transfer area ensuring high effectiveness of the water vapour transfer from flue gas to the air.

An economic evaluation of the *HRS* reveals that investment into the *HRS* is effective: the payback time is about 4 years and, during the operation lifetime of the *HRS*, the cogeneration plant gains additional 10.4 million Euro, i.e. about one third of the new plant cost. Moreover, in case the heat is provided by some producers for a one big heat consumer, there is possibility to increase the income from an additional heat selling; a lower heat costs would allow to compete other producers taking over their heat production capacities.

BEC	bare erected cost
COP	coefficient of performance
E	specific heat recovered in both economizers
Ed	specific heat recovered in dry economizer
Ec	specific heat recovered in condensing economizer
HHV	high heating value
HRS	heat recovery system
ΔH°	mass part of hydrogen in dry wood
LHV	low heating value
ORC	Organic Rankine cycle
P	power
P_0	atmospheric pressure, [mbar]
R	specific heat recovered in regenerator
Q	heat, [MW]
TPC	total cost of project
TOC	total overnight cost
TASC	total-as-spent cost
WWC	woodfuel water content
ΔW	water mass fraction
h_{l-g}	water latent heat, [kJ/kg]
l	specific losses
r	ratio
p	water partial pressure, [mbar]
q	specific heat
t	temperature, [°C]
η	efficiency
ω	specific humidity, [kg/kg]

Subscripts

ad	additional
b	burning
c	condensing
d	dry
e	energy
el	electrical
in	input
m	mechanical
out	output
st	stack
T	thermodynamic
wn	own
0	index shows that wood is fully dry

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