ASPECTS OF CONSTRUCTIVE AND THERMO-ECONOMIC ANALYSIS OF STEAM TURBINES USED FOR SOLID BIOMASS VALORIZATION

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Abstract - In energy valorization by burning solid biomass fuels, the achieved thermal power is relatively low, so that maximum electrical power is about 2 MW for agricultural waste and 5 MW for wood waste. Low power turbine construction involves solving a multitude of functional and structural problems. This paper examines different solutions for steam turbines up to 2 MW electrical power.
The thermo-economic analysis is carried out for a 200 kW steam turbine used for valorizing energy willow, resulting from its harvesting experience in Romania.

Keyword biomass valorization, steam turbines, thermo-economic analysis.

Notations:
m - mass flow rate [kg/s]
ε - admission degree [-]
c - absolute velocity of steam [m/s]
u - peripheral velocity [m/s]
d - mean diameter [m]
l - height/length of nozzles/blades [m]
v - specific volume [m^3/kg]
H - mass flow coefficient [-]
t- section area factor [-]
α - nozzle exit angle [rad]
n - turbine speed [rpm]
Indexes:
1 – exit from nozzles
2 – exit from blades *a*–nozzle
p - blade
ef – effective

1. INTRODUCTION

The steam turbines used in power plants that burn biomass from agricultural sources have some characteristics imposed to them by the low thermal potential of these sources. The main features of such turbines could be evaluated after a comprehensive study of the solutions available for this domain and of the parameters of the steam generators that have biomass as fuel.

Most of the functional and constructive features of the steam turbines derive from the enthalpy drop available from the live steam conditions and from the exit parameters, which in turn, depend on the cooling agent for the condenser or from the heat demand of the consumer in the case of back-pressure turbines and on the effective power at the coupling with the electrical generator, which is the product of enthalpy drop, mass flow rate and effective efficiency of the expansion process in the steam turbine.

2. FUNCTIONAL PARAMETERS OF THE STEAM TURBINES

The most important parameter is the specific volume of the live steam, which depends on the two nominal parameters: pressure and temperature.

The specific volume of the live steam or even better of the steam that leaves the first stage nozzles, coupled with the minimal height of the flow path, which is technologically feasible (usually 10 mm), impose the rotational speed of the turbine. That parameter can be determined from the flow rate equation:

$$\dot{m}_a \cdot v_1 = \pi \cdot d_1 \cdot l_{a1} \cdot \varepsilon \cdot c_{1a} \cdot \mu_a \cdot \tau_a \quad (1)$$

coupled with the optimal velocities ratio:

$$\left(\frac{u}{c_1}\right)_{opt} = k_x \cdot \frac{\cos(\alpha_{1ef})}{2 \cdot (1-\rho)} \quad (2)$$

where: k_x is the velocity ratio factor (usually $k_x = 0.9$), while peripheral velocity *u* is given by

$$u = \pi \cdot \frac{n}{60} \cdot d \quad \text{[m/s]}. \quad (3)$$

The rotational speed of the steam turbine can be determined by the admissible value for the tension at the root of the last stage blades due to centrifugal forces, since they are proportional with the square of the speed:

$$\sigma_{cf} = K_f \cdot \omega^2 \cdot \pi \cdot l_p \cdot d \quad \text{[Pa]} \quad (4)$$

where K_f - is a form/shape factor that takes into account the variation in area of the section of the blade profile from root to tip. Noting the area of the exit section of the steam path by:

$$S_e = \pi \cdot l_p \cdot d \qquad [\mathrm{m}^2] \qquad (5)$$

we get

$$\sigma_{cf} = K_f \cdot \omega^2 \cdot S_e \approx \omega^2 \cdot \frac{m \cdot v_c}{c_{2a}} \qquad (6)$$

where v_c is the specific volume of the steam at the exit from the last stage and c_{2a} is the exit axial velocity.

The enthalpy drop for a stage having a degree of reaction of ρ is [3]

$$H_{st} = k_h \cdot (1-\rho) \cdot \left(\frac{d \cdot n}{k_x \cdot \varphi \cdot \cos(\alpha_1)} \right)^2 \quad [\mathrm{J/kg}] \ (7)$$

where k_h is a numerical coefficient that takes into account the energy recovery from the upstream stage and the units transformation, while φ is the velocity reduction factor in the nozzles, α_1 being the angle of the absolute velocity at the nozzle outlet.

From studying the above equations, which are available for the axial flow steam turbines, the main influencing functional factors upon the constructive solutions for the steam turbines can be easily observed:

- the degree of reaction is directly influencing the number of stages and the constructive solution (diaphragms and discs versus drum type rotor);
- the rotational speed influences the number of stages and the tension values due to centrifugal forces;
- the mean diameter and the length of the blades give the main dimensions of the turbine stages and the values of the tension at the root of the longest blades.

For other type of steam turbines used for energy valorization of biomass similar relations can be written, with the same influences on the constructive solutions to be chosen from.

1. CONSTRUCTIVE SOLUTIONS OF STEAM TURBINES FOR ENERGY FROM BIOMASS

The constructive solutions are greatly influenced, as stated before, by the magnitude of the thermal resource to be valorized, which is given by the following main parameters:

- the power of the driven electrical generator and the magnitude and the load type of the thermal power in the case of cogeneration;
- the parameters of live steam from the boiler (pressure, temperature and mass flow rate);
- the parameters of the steam at the exit from the steam generator;
- the rotational speed;
- the functional type derived from the degree of reaction (impulse type or reaction type).

For the smallest units having up to 200 kW, micro-turbines solutions are available:

Table 1. Single stage steam micro-turbines

Nominal Power [kW]/ speed [rpm]	Live steam parameters [bar]/[ºC]	Exit parameters [bar]/[ºC]	Constructive solution	Observations
50..250/3000	4..12/140..250	2/sat.	Patented "bristles" solution; tangential inlet centripetal flow	[5] steam consumption 1.5..4[t/h]
15/26000	10..12/200..220	0.1/sat	Radial flow	[1] steam consumption/ rate 0.04[kg/s]/ 9.8[kg/kWh]
275/n.a.	13.8/n.a.	0.138/sat	Radial flow	steam consumption/ heat rate 0.5[kg/s]/3.9[MJ/kWh]

For the larger power range, from 2 to 5 MW the functional and constructive solutions are those derived from the industrial steam turbines some examples are shown below:

Table 2. Multiple stage steam turbines

Nominal Power [kW]/speed [rpm]	Live steam parameters [bar]/[ºC]	Exit parameters [bar]/[ºC]	Constructive solution	Observations
3000/ 11543 / 1500	21/275	0.23/sat.	Axial flow reaction drum type with Rateau first stage	steam consumption/ rate 6.41[kg/s]/n.a. [4]
4.8/3000	42/425	0.8/sat	Axial flow impulse type; diaphragm and discs	steam consumption; efficiency elec./cogen. 8.33[kg/s];18.1%/93%
1000/10500 /1500	35/435	0.1/sat	Axial flow reaction drum type with Rateau first stage and controlled extraction	steam consumption /heat production 2.78[kg/s]/4[MWt]

From the examples mentioned above the last is illustrative for the use of industrial type steam turbine for biomass valorization. In comparison to other type of turbines which have smaller number of stages, as in the case of impulse type turbines, (or just one velocity compounded stage, for Curtis type turbines), which have lower thermodynamic efficiency, the turbine presented in figure 1 provides maximum efficiency, that is practically achievable, thus allowing faster investment return and better utilization of the biomass resources, in this particular case forest chips [2].

Feasibility studies have shown that the optimal power of biomass powered power plant is 1 MW of electricity to 4 MW of thermal power, in the following conditions:

- production of energy under status of privileged supplier (8000 hours of electrical power and 5000 hours per year of thermal power).
- prices of forest chips and freight rates to be kept to a minimum.

Larger power plants are less efficient because of:
- smaller usage of fuel, for there is small to none opportunity for the consumption of thermal energy, which is then released in the environment;
- reduced environmental advantages due to the effect of transport over long distances, combined with excessive wear of roads; to supply an electric power plant of 5 MWe with fuel, a large truck of fuel is necessary each hour;
- the storage large amounts of ash.

For the intermediate power range 500 kW to 1000 kW, the functional and constructive solutions are mixed, combining elements from the high speed single constructions with lower speed multistage, "classical" design steam turbines.

An example of small power range steam turbine integration into a complex technological flow of a power station for energy valorization of Swedish willow is given in the Figure. 1.

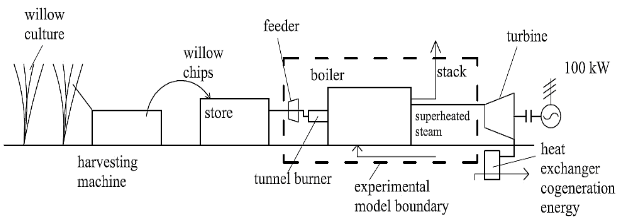

Fig. 1. Complex technological flow of the 100 kW power station

For the 100 kW range two calculations were made: one for an axial flow, high speed (n >3000 rpm) and one for radial flow solution using the method presented in [6], for the same inlet parameters and outlet parameters of the steam (6 bar/ 220°C and 2 bar backpressure).

The axial type steam turbine in order to use the whole enthalpy drop with maximum efficiency should have more than stage, as shown in the graph bellow, where the series correspond to1 stage, 2 stages and 4 stages respectively of the Rateau impulse type.

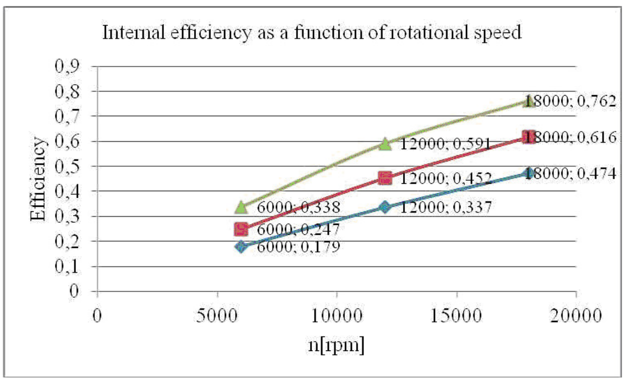

Fig.2. Internal efficiency as a function of rotational speed

Increasing the number of stages complicates the construction of the steam turbine and thus the cost of the initial investment. Using a velocity compounded solution, the Curtis type stage, lowers the internal efficiency by 20% to 50% with regard to the Rateau type stage.

In the case of the radial type single stage steam turbine, the whole enthalpy drop could be processed in only one stage. A method to estimate the main constructive dimensions of the steam turbine is given in [6].

The first step is to calculate the specific speed of the turbine:

$$n_s = \frac{\frac{2 \cdot \pi \cdot n}{60}\sqrt{\dot{V}}}{H_t^{0.75}} \qquad (8)$$

where n_s is the specific speed,
n is the rotational speed [rpm],
$\dot{V}$ is the volumetric flow rate[m^3/s] (that is the mass flow rate times the specific volume of the steam) and H_t [kJ/kg] is the theoretical enthalpy drop in the stage. For the maximum efficiency the specific speed should be around 0.5 [6].

3. THERMO-ECONOMIC ANALYSIS OF A SMALL BIOMASS FUELLED POWER PLANT

3.1 Case study

The objective of the case study is to define the architecture of a small power-plant biomass fuelled and to asses its technical and economic performances.

The micro power plant is composed from:
A superheated live steam generator (p_0=25 bar, t_0= 275 °C, t_{al}=120 °C) fuelled by dry chopped energy willow;
- A steam turbine (P_e= 200 kWe, p_c=0.15 bar, n=15000 rpm);
- An electric generator with 4 poles coupled to the turbine trough a gear;
- A deaerator supplied with live steam trough a lamination valve;
- The condensate pump and the feed-water pump.

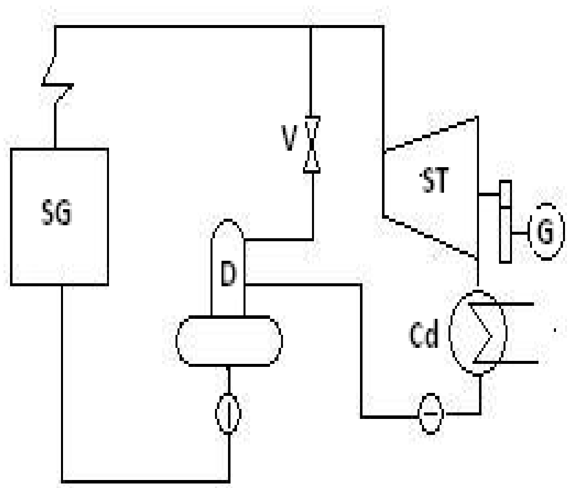

Fig.3. Microturbine CHP system

3.2. Technical performances

In order to produce 200 kWe, the steam turbine-generator needs a flow-rate of 0.444 kg/s to expand with an internal efficiency η_i=0,65. Summing the necessary flow for the deaerator, the steam generator must supply an amount of 0.495 kg/s, using the heat generated by the combustion of 2420 t/year of energy willow chops with LCV=16000 kJ/kg, with a global efficiency η_{sg}=0,9.

Taking into account that the average yield of the energy willow crop is about 50 t/hectare and the harvest period is every 3 years, the overall cultivated area should be equal to 150 hectares.

3.3. Economic analysis

The economic analysis is carried on a period equal to the lifetime expectance of the equipments (usually 15 years). The cash-flow source is represented by the money value of the available electricity generated during this period. There are two components: the market price (p_{el}= 40 €/MWh) and the support scheme for the energy produced from renewable sources (3 green certificates of p_{gc}=27-52 €/MWh).

The expenses are represented by the annual return of the investment, the interest (if the investment cost is covered even partially by a loan), the fuel cost, O&M cost, insurance, etc.

Considering an annual discount rate (a), it is possible to compute the economic indicators of the case, such as: payback time (T_s), net present value (NPV), internal rate of return (IRR). The conditions for a good micro gas turbine system are: NPV > 0, IRR > a, T_s < lifetime and related to the investor satisfaction.

$$NPV = \sum_{t=0}^{n} \frac{V_t - C_t}{(1+a)^t} \qquad (9)$$

IRR = a^* (10) for

$$NPV = \sum_{t=0}^{n} \frac{V_t - C_t}{\left(1+a^*\right)^t} = 0 \qquad (11)$$

$$\sum_{t=0}^{n_{\min}=T_s} (V_t - C_t) \geq 0 \qquad (12)$$

where: - V_t – revenues of year t; C_t – expenses of year t; - n – microturbine system lifetime.

The study case is based on the installation of a TPP producing 200 kWe and delivering to the network 190 kWe operated in integration with the forest activity (energy willow crop). The annual operation period was estimated at 8000 hours.

The input figures for the economic analysis are:

- Specific capital cost I_{sp} = 4000 €/kW$_i$;
- O&M costs $C_{O\&M}$ = 40 €/MWh$_e$;
- Energy willow price p_{ew} = 20 €/t;
- Electricity market price p_E = 40 €/MWh$_e$;
- Green certificate price p_{GC} = 52 €/kWh$_t$;
- Discount rate a = 10%;
- Planned payback period T_p = 7 years.

The results of economic analyze are shown in table 2.

Table 3. Economic figures of the TPP

T_s, years	NPV, €	IRR, %
8,8	229.432	10.87

Analyzing these figures, we can draw the conclusion that the project is feasible. However, a slight slippage of a single input data (such as the value of the green certificate that can decrease, if the amount of electricity produced from renewable sources increases), can easily bring looses to the project and put the owner company in a difficult situation.

In order to avoid these situations, the best approach is to find a heat consumer in the plant vicinity, in order to have the second cash-flow, represented by the value of the sold thermal energy.

5. CONCLUSION

The functional and constructive solutions of the steam turbines for biomass valorization are chosen according to the specific parameters of each case, in order to get optimal values for the technological and the economic performances of the power plants. For a better use of the biomass potential the cogeneration power plants are widely spread and in some instances encouraged by state founded incentives, such as the “green certificates”.

In the case of small power range novel types and solutions for the steam turbines are proposed, some of which have very promising efficiency values.

In the mid range cases other thermal energy solutions could be used, such as the Organic Rankine Cycle (ORC) turbine installations, which eliminate the main disadvantage of the water based cycles, the lower density values.

And last but not least, the economic analysis has the predominant role in the decision making process of choosing the right type of turbine installation and getting the funding from the potential investors, which are of different scale that in the case of large fossil fuel power stations.

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