A NEW APPROACH IN COMBINED HEAT AND POWER STEAM TURBINES THERMODYNAMIC CYCLES COMPUTATIONS

by

Vojin R. GRKOVIĆ[a*]***, Dragoljub S. ŽIVKOVIĆ***[b]***, and Milana M. GUTEŠA***[a]

[a] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia
[b] Faculty of Mechanical Engineering, University of Niš, Niš, Serbia

Original scientific paper
DOI: 10.2298/TSCI120503178G

This paper presents a new approach in mathematical modeling of thermodynamic cycles and electric power of utility district-heating and co-generation steam turbines. The approach is based on the application of the dimensionless mass flows, which describe the thermodynamic cycle of a combined heat and power steam turbine. The mass flows are calculated relative to the mass flow to low pressure turbine. The procedure introduces the extraction mass flow load parameter ν_h *which clearly indicates the energy transformation process, as well as the co-generation turbine design features, but also its fitness for the electrical energy system requirements. The presented approach allows fast computations, as well as direct calculation of the selected energy efficiency indicators. The approach is exemplified with the calculation results of the district heat power to electric power ratio, as well as the cycle efficiency, vs.* ν_h*. The influence of* ν_h *on the conformity of a combined heat and power turbine to the grid requirements is also analyzed and discussed.*

Key words: *district heating turbines, co-generation turbines, combined heat and power turbines, thermodynamic cycles, energy efficiency, electric power computation*

Introduction

The most frequently used approach in developing procedures for calculations of thermodynamic cycle characteristics, like electric power and heat rate, is based on the calculation of mass-flows to feed water heaters relative to the live steam mass-flow. Thus, the equations of energy balance for each feed water heater have to be set, where all mass-flows are relative to the live steam mass-flow. The form of equations is (*e. g.* for the heater No. 5 in the scheme presented in fig. 1):

$$m_{e5} = (m_{LPTo} + m_{e7} + m_{e6}) \frac{h_{H5o} - h_{H5i}}{h_{e5} - h_{e5}^{'}} \tag{8}$$

The values m_{LPTo}, m_{e5}, m_{e6} and m_{e7} are mass flows to the condenser, as well as to the heaters No. 5 to 7, all relative to live steam mass flow, respectively.

---

* Corresponding author; e-mail: vojingr@uns.ac.rs

After setting the equations for all feed water heaters and after solving the system of the equations, one can calculate the electric power of the steam turbine per unit mass flow at the high pressure turbine inlet, using the equation:

$$L_{Te} = 1\cdot(h_{HPTi} - h_{e1}) + (1 - m_{e1})(h_{MPTi} - h_{o2}) + \\ +(1 - m_{e1} - m_{e2})(h_{e2} - h_{e3}) + ...\left|\left(1 - \sum_{j=1}^{7} m_{ej}\right)(h_{e7} - h_{LPTo})\right]\eta_m \eta_G \tag{2}$$

The values for m_{e1} to m_{en} (in the example from fig. 1, to m_{e7}) are the real solution of the system of equations exemplified by eq. (1). The values h_{e1} to h_{e7} are the enthalpies of the steam at the corresponding extraction points in the turbine, and η_m and η_G are turbine mechanical and generator efficiency, respectively. Finally, the unknown mass flow at the high pressure turbine (HPT) inlet is calculated on the basis of the required electric power:

$$M_{HPTi} = \frac{P_e}{L_{Te}} \tag{3}$$

Some procedures are based on the calculation of the full mass flows, instead of the mass flows relative to the live steam mass flow, where the live steam mass flow is taken as a known or supposed value. A comprehensive analysis of the district heating turbines cycles is presented in [1]. One special procedure for steam turbines cycle calculation is presented in [2]. Although very clever, these procedures, when applied to combined heat and power (CHP) turbines, create significant difficulties that result in a lot of computation, spending considerable computer time. This is particularly visible during the simulation procedures [3]. Sometimes, significant efforts are necessary for optimization of only one parameter [4]. This is caused by the fact that the steam flow extracted for co-generation purposes is the function of the required heat power P_t. On the other hand, the heat power P_t for the steam turbine thermodynamic cycle calculation represents an additional border condition that must be satisfied [5].

New approach in CHP steam turbines thermodynamic cycles computations

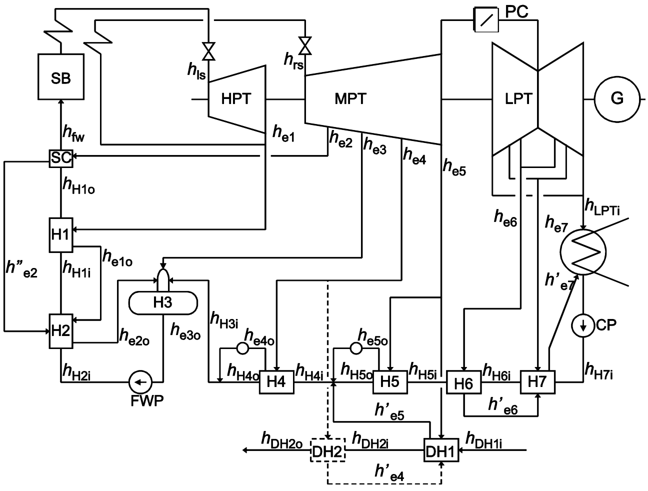
In order to solve the problem mentioned above in another way, we have calculated all mass flows relative to the total mass flow entering the low pressure turbine (LPT). If we assume the heat balance scheme in fig. 1 as the reference one, the mass flows extracted from the turbine to district heaters are determined by the equations (second district water heater is assumed as another variant):

$$M_{DH2} = \frac{P_{t2}}{h_{e4} - h_{e4}^{'}} \tag{4}$$

$$M_{DH1} = \frac{P_{t1} - \dot{M}_{DH2}(h_{e4}^{'} - h_{e5}^{'})}{h_{e5} - h_{e5}^{'}} \tag{5}$$

After introducing the value $v_h = \Sigma M_{DH}/M_{LPT}$ as the ratio of the total mass flow extracted to the district heaters (M_{DH}) to the mass flow to the LPT (M_{LPT}), we can set the energy balance equations for all feed water heaters, as well as for all mixing points in the feed water system, with the mass flows relative to M_{LPT}.

Figure 1. Example of the CHP steam turbine heat balance scheme



The equations setting procedure is exemplified by the energy balance equation for the heater No. 1, as:

$$h_{H1i}\left(1+\nu_h+\sum_{j=1}^{5}\mu_{ej}\right)+h_{e1}\mu_{e1}=h_{H1o}\left(1+\nu_h+\sum_{j=1}^{5}\mu_{ej}\right)+h_{e1o}\mu_{e1} \tag{6}$$

where μ denotes the fluid mass flow relative to the total mass flow at the inlet of LPT, as: $\mu_{e1}=M_{e1}/M_{LPT}$, $\mu_{e2}=M_{e2}/M_{LPT}$, …, $\mu_{e7}=M_{e7}/M_{LPT}$.

The enthalpy increase, as the feed water is passing through the feed water pump, is calculated on the basis of the isentropic enthalpy increase and the pump efficiency.

In the above system of equations the unknown values are all the mass flows extracted from the turbine for feed water heating relative to the mass flow at the inlet of LPT, and the enthalpies at the inlet of the feed water heaters No. 2, 3 and 4. By solving the system of equations we determine the real values of μ_{e1} to μ_{e7}, as well as h_{H2i}, h_{H3i}, and h_{H4i}.

Then the turbine electric power relative to the total mass flow at the inlet of LPT is calculated by the equation:

$$\begin{aligned}\Lambda_{Te}={}&\left(1+\nu_h+\sum_{j=1}^{5}\mu_{ej}\right)(h_{HPTi}-h_{e1})+\left(1+\nu_h+\sum_{j=2}^{5}\mu_{ej}\right)(h_{MPTi}-h_{e2})+\\&+\left(1+\nu_h+\sum_{j=3}^{5}\mu_{ej}\right)(h_{e2}-h_{e3})+\left(1+\nu_h+\sum_{j=4}^{5}\mu_{ej}\right)(h_{e3}-h_{e4})+\\&+(1+\nu_{DH2}+\mu_{e5})(h_{e4}-h_{e5})+(h_{e5}-h_{e6})+\\&+(1-\mu_{e6})(h_{e6}-h_{e7})+(1-\mu_{e6}-\mu_{e7})(h_{e7}-h_{LPTo})\end{aligned} \tag{7}$$

The unknown value of the mass flow to the LPT is determined for the given electric power of the turbine P_e from the equation:

$$M_{LPT}=\frac{P_e}{\Lambda_{Te}} \tag{8}$$

The live steam mass flow is calculated by using the mass balance equation as:

$$M_{HPTi} = M_{LPT}\left(\nu_h + 1 + \sum_{j=1}^{5}\mu_{ej}\right) \tag{9}$$

The efficiency of the energy transformation process in the co-generation steam turbine is calculated using the equation:

$$\eta_{CST} = \frac{P_e + P_t}{Q_b} \tag{10}$$

The value Q_b is the total heat amount brought in the process, determined by the equation:

$$Q_b = M_{LPT}\left[\left(\nu_h + 1 + \sum_{j=1}^{5}\mu_{ej}\right)(h_{HPTi} - h_{fw}) + \left(\nu_h + 1 + \sum_{j=2}^{5}\mu_{ej}\right)(h_{MPTi} - h_{e1})\right] \tag{11}$$

Since two independent indicators are necessary for adequate judgment of the energy transformation process in the co-generation steam turbines [6], we can use the turbine electric power to the turbine heat power ratio, denoted with s_e as the second one. Therefore, finally we obtain:

$$s_e = \frac{P_e}{P_t} \tag{12}$$

Results and discussion

The referent cycle for the computations and analysis is in the range of modern district heating steam turbines. The live steam conditions are: p_{HPTi} = 18.0 MPa, t_{HPTi} = 540 °C; the reheat steam conditions are: $p_{\ MPT}$ = 4.2 MPa, t_{MPTi} = 540 °C; the low pressure turbine exhaust pressure is: p_{LPTo} = 5.6 kPa. There are 7 feed water heaters in the cycle, according to the scheme presented in fig. 1.

The analysis was performed with variation of the mass flow to the inlet of the low pressure turbine, keeping constant the turbine heat power. Therefore, the above defined extraction mass flow load parameter $\nu_h = \Sigma M_{DH}/M_{LPT}$ was entered as the known parameter in the analysis. Other steam turbine cycle parameters can also be considered in computations as the known parameters. Figure 2 presents the computed influences of the live steam pressure and the steam extraction mass flow load parameter ν_h on the turbine electric power to the heat power ratio, as well as on the efficiency of the energy transformation process in the co-generation steam turbine, as defined by eqs. 12 and 10, respectively. The equal distribution on both district heating water heaters was accepted for the analysis.

The occurrence analysis was performed on the basis of the first law of thermodynamics according to the equation:

$$e_p = \frac{(P_t + P_e + Q_l) - Q_b}{Q_b} \tag{13}$$

where e_p denotes the error in percents and Q_l denotes the heat transferred in the condenser.

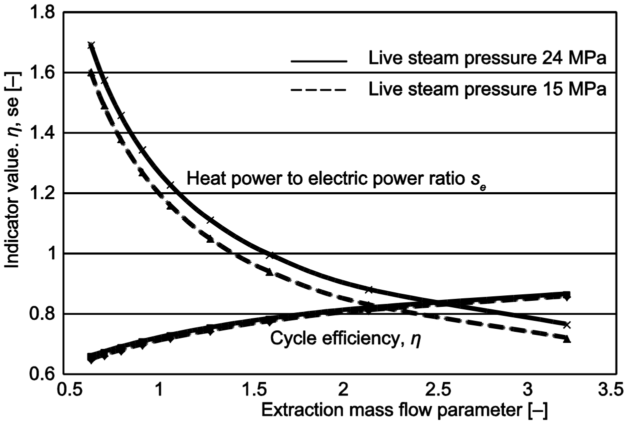


Figure 2. Computed correlations of the CHP steam turbine process efficiency and the electric power to the heat power ratio versus live steam pressure, as well as the steam extraction mass flow load parameter v_h

The error, obtained within performed calculations, was situated within the interval of $-0.4 < e_p < 0.3$ percent. In the case of the live steam pressure of 15 MPa the error amounted to between –0.4 and –0.3 percent, while in the case of the live steam pressure of 24 MPa the error amounted to between 0.1 and 0.3 percent. Generally, the performed calculations show that the error is situated within the interval of $-0.4 < e_p < -0.3$ percent for the $v_h < 0.5$.

The increase in v_h produces a significant increase in the co-generation steam turbine process efficiency. Thus, v_h as the indicator of the heat extraction mass flow load is in tight correlation with the efficiency of the energy transformation process in the co-generation steam turbine. On the other hand, the increase in v_h also produces a significant decrease in the co-generation steam turbine electric power. Although we can have a better process from the energy efficiency point of view, by increasing v_h we can have less electrical energy to sell. Since the electrical energy is more expensive than the heat, the parameter v_h also has the importance for overall economy of the co-generation power plant.

It should be noticed that the size of certain parts of the equipment depends on the value of v_h, either through the value of the thermal power P_t, or through the mass flow entering low pressure turbine [7]. Since the size of the low pressure turbine is directly affected by the entering mass flow, which is particularly important in the case of district heating turbines [8], the size is also affected by the value of the v_h parameter.

The computation results show greater sensitivity of the indicators values to the change of the extraction mass flow load parameter v_h, than to the change of live steam pressure, as can be seen in fig. 2. In exemplified computations, the co-generation steam turbine heat power P_t, as well as all the other thermodynamic cycle parameters independent of the live steam pressure and heat extraction mass flow load parameter, are kept unchanged.

The numerical value of v_h can also indicate the fitness of the CHP steam turbine to the electrical energy system requirements. In the case of the modern steam turbines with the heat extractions like those described in [9], there are two intervals of the turbine electric power change that are very important for the adaptation of the turbine to the electric system conditions [10]. The interval ΔP_{e1} represents the difference between the co-generation steam turbine maximal electric power and the electric power in the point of the maximal heat power by maximal live steam flow (fig. 3). The value of ΔP_{e1} represents the power shortage conditioned by the CHP operation for meeting the needs of the electrical system. The value of ΔP_{e1} is influenced by many parameters, such as: the co-generation steam turbine thermal power, the number of steam extractions for co-generation purposes, the pressure level of each extraction, the low pressure turbine (LPT) exhaust pressure, and others.

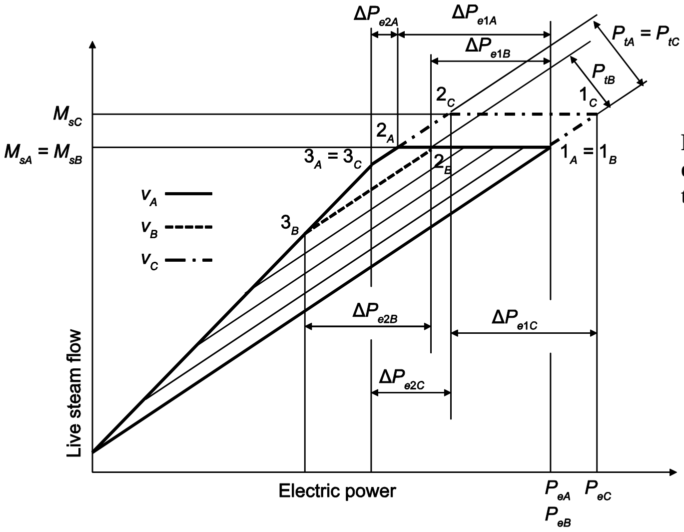


Figure 3. Effect of decreasing v_h on operation diagram of CHP steam turbine (schematic)

The interval ΔP_{e2} represents the difference between the maximal and the minimal electric power of the co-generation steam turbine by the maximal heat power. The value of the interval ΔP_{e2} represents the ability of the CHP steam turbine to adjust low loads of the electrical energy system without the reduction of the heat power. However, the value of ΔP_{e2} is directly affected by the value of v_h. The value of ΔP_{e2} can be increased compared to the referent case (A) in fig. 3 by the adoption of a lower value of v_h. This is possible either by the reduction of the heat power P_t of the design turbine (case B in fig. 3), or by the increase in the design live steam flow, and consequently the flow to the low pressure turbine (case C in fig. 3). In case B, we would have less heat power to sell, while in case C we would possibly have a surplus of electric power.

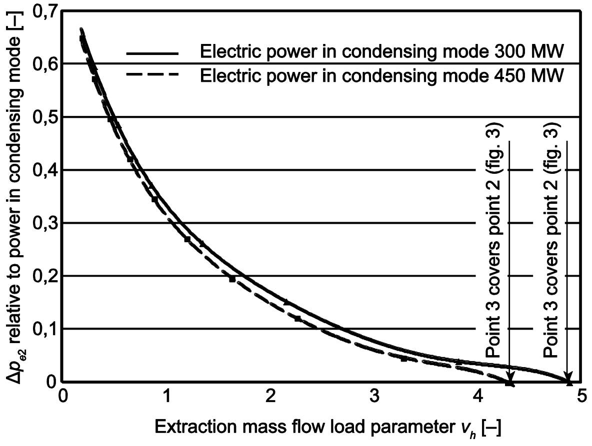


Figure 4. Computed dependence of the electric power interval ΔP_{e2} on the heat extraction mass flow load parameter v_h

The computed correlation of the electric power reduction interval ΔP_{e2} and the heat extraction mass flow load parameter v_h at the design point (determined with the maximal thermal power P_t and the maximal boiler live steam flow M_s) is plotted in fig. 4. The smallest value of v_h is conditioned by the smallest value of the design steam turbines heat power P_t. On the other hand, the largest value of v_h is in the point where the design value of P_t is so large that no reduction of electric power independently of the heat power is possible. This is when point 3 falls in point 2 in fig. 3. The position of point 3 is arbitrarily selected at the point when steam flow to the LPT equals 20% of the flow in the condensing mode of operation. The dependence of ΔP_{e2} on v_h is to a certain extent influenced by the size of the equipment expressed through the steam turbine electric power in the condensing mode of operation.

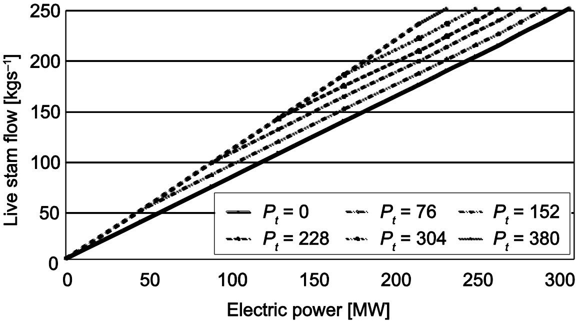


Figure 5. Calculated example of the operation diagram for the steam turbine with one steam extraction

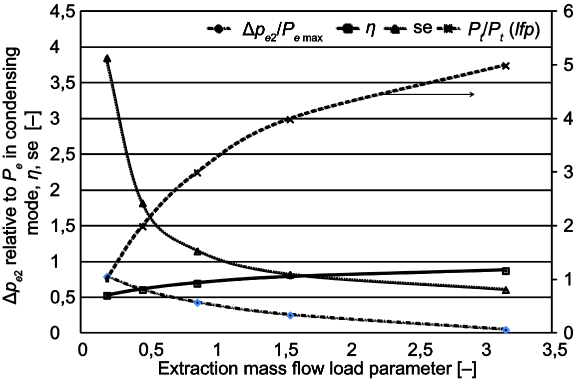


Figure 6. Important process indicators for the steam turbine with one steam extraction

In the computations performed for the results presented in figs. 2 and 4, the electric power loss that occurs when the heat power differs from those in loss-free-point is not included. Figure 5 presents the calculated example of the operation diagram for the district heating turbine electric power of 308 MW in the condensing mode of operation, and thermal power in loss-free-point of 76 MJ/s. The live steam conditions of the turbine are: p_{HPTi} = 18.0 MPa, t = 540 °C; the reheat steam conditions are: p_{MPTi} = = 4.2 MPa, t = 540 °C. There are 7 feed water heaters and one steam extraction for the district heating. It is supposed that the control of the heat power in the DH system by changing the water flow at the constant value of the outgoing water temperature equals 135 °C. The thermal power of the turbine is higher than those in the loss-free-point obtained by closing the butterfly valve between MPT and LPT. The electric power loss that occurs when the heat power differs from those in the loss-free-point is included here.

Figure 6 shows all above considered indicators versus heat extraction mass flow load parameter v_h, calculated on the basis of the operation diagram from fig. 5, which corresponds to the district heating turbine with one extraction. The considered indicators of the energy transformation process in the turbine are efficiency η and turbine electric power to the turbine heat power ratio se. The ratio of ΔP_{e2} and turbine electric power in the condensing mode of operation is used as an indicator of the turbine fitness to the electric energy system requirements. Finally, the ratio of the actual heat power P_t and heat power at the loss-free-point is used as a district heating turbine design indicator. Although the shape of the indicators dependence corresponds to those for the turbine with two extractions from figs. 2 and 4, their values are more adequate, since the loss of the electric power due to control of the heat power has been taken into account.

Conclusions

The paper outlines a new procedure, as well as an advanced computation model, for the calculation of the thermodynamic cycles and the electric power of the co-generation steam turbines. The approach is based on the application of the dimensionless mass flows, which describe the thermodynamic cycle of a CHP steam turbine. The mass flows are calculated relative to the mass flow to low pressure turbine. The heat extraction mass flow load parameter ν_h is introduced in the model. The model appears more convenient compared to the standard ones. The most important conclusion is that the extraction mass flow load parameter ν_h is significant for the overall process of energy transformation in the turbine, as well as for the overall co-generation steam turbine economy. Moreover, this parameter has a considerable importance for the co-generation steam turbine design, as well as for its fitness to the technological requirements of the considered electric energy system.

Acknowledgments

This work is partially based on the results of the project titled “Development of CHP demonstration plant with gasification of biomass”, which is partially financed by the Serbian Ministry of Science and Technology (Project No. 33049).

Nomenclature

h_i – enthalpy of the steam, [kJkg $^{-1}$]
L_{Te} – electric power of the steam turbine per unit mass flow, [kJ kg^{-1}]
M – mass flow, [kg s $^{-1}$]
m_i – relative mass flow, [–]
P_e – required electric power, [kW]
P_t – required heat power, [kW]
ΔP_{e1} – power shortage conditioned by the CHP operation for meeting the needs of the electric system, [kW]
ΔP_{e2} – difference between the max. and the min. electric power of the co-generation steam turbine by the max. heat power, [kW]
p – pressure, [MPa]
Q_b – total heat amount brought in the process, [kW]
Q_l – heat transferred in the condenser, [kW]
s_e – turbine electric power to the turbine heat power ratio, [–]
t – temperature, [K], [$^{\circ}$C]

Greek symbols

η – efficiency of the energy transformation process, [–]
η_{CST} – co-generation steam turbine efficiency, [–]
η_G – generator efficiency, [–]
η_m – turbine mechanical efficiency, [–]
Λ_{Te} – turbine electric power relative to the total mass flow at the inlet of LPT, [kWkg^{-1} s]
μ – fluid mass flow relative to the total mass flow at the inlet of LPT, [–]
ν_H – ratio of the total mass flow extracted to the district heaters (M_{DH}) to the mass flow to the LPT (M_{LPT}), [–]

Acronyms

CHP – combined heat and power
CP – condensate pump
DHi – district heater
FWP – feed water pump
Hi – feed water heater
HPT – high pressure turbine
LPT – low pressure turbine
MPT – middle pressure turbine
SB – steam boiler

References

[1] Horlock, J. H., *Co-Generation – Combined Heat and Power (CHP),* Krieger Publishing Company, Malabar, Fla., USA, 1997

[2] Savić, B., Computer Program TURBOEX for the Computation of Performances of Fossil Fuel Co-generation Plants with Extraction Steam Turbines, in: *Mathematical Modeling and Computer Simulation of Processes in Energy Systems* (ed. K. Hanjalic), Hemisphere Publishing Corporation, 1991, pp. 815-828
[3] Grković, V., Simulation of Stationary Operational Conditions of Condensing Turbines Combined with District Heating (in German), *BWK, 39* (1987), 7/8, pp. 349-354
[4] Grković, V., Selection of the Optimal Extraction Pressure for Steam from a Condensation-Extraction Turbine, *Energy, 15* (1990), 5, pp. 459-465
[5] Janicka, J., Calculations Procedure for Thermal Power Plants Processes (in German), *BWK, 42* (1990), pp. 505-513
[6] Grković, V., Energy-Efficiency Improvements by Joint Operation of Two DH Systems Using Old Condensing Turbines, *Energy, 22* (1997), 11, pp. 1099-1102
[7] Grković, V., Optimizations for District Heating of Belgrade from the Kolubara Energy and Industrial Complex, *Energy, 14* (1989), 11, pp. 747-756
[8] Haimow, V. A. *et al.*, Low Flow Rate Regimes and LPT Strength of T-250/300-23.5 District Heating Steam Turbine (in Russian), Energy-Atom-Publisher, Thermal Energy (ISSN 0040-3636)
[9] Schenck, K, Zorner, W. E., Advanced Steam Turbines with Heat Extraction Walsum and Herne Power Plants, in: *Co-Generation and Combined Cycle Plants – Design, Interconnection, and Turbine Applications* (Ed. J. W. Schroeder), The American Society of Mechanical Engineers, New York, 1990, pp. 59-67
[10] Grković, V., *Technological Fundaments of Co-Generation Steam Turbines Control* (in Serbian), Futura Publikacije, Novi Sad, Serbia, 1995

Paper submitted: May 3, 2012
Paper revised: July 4, 2012
Paper accepted: July 12, 2012