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EVALUATION OF PERFORMANCE PARAMETERS OF THE EXTRACTION CONDENSING TYPE POWER UNIT AT A COMBINED HEAT AND POWER PLANT

SUMMARY

Fundamental relationships defining the effectiveness of regeneration processes in steam power stations were precisely formulated. Characteristics of a extraction condensing type power unit with the regeneration systems at a combined heat and power plant were obtained experimentally for a wide range of operating loads. The energy analysis would yield the optimal range of performance parameters of the power unit for the heating and condensing working modes.

***Keywords**: steam power station, power plant, combined heat and power plant, extraction condensing type power unit, regeneration system*

OCENA EFEKTYWNOŚCI PRACY BLOKU UPUSTOWO-KONDENSACYJNEGO ELEKTROCIEPŁOWNI

We wstępie artykułu uściślono podstawowe zależności w zakresie efektywności procesu regeneracji w siłowni parowej. Następnie na podstawie badań eksperymentalnych przeprowadzonych w szerokim zakresie obciążeń ruchowych zestawiono charakterystyki bloku upustowo- kondensacyjnego elektrociepłowni z funkcjonującym układem regeneracji. W wyniku przeprowadzonej analizy energetycznej określono zakres optymalnych parametrów pracy bloku zarówno dla ciepłowniczego, jak i dla kondensacyjnego trybu pracy.

***Słowa kluczowe**: siłownia parowa, elektrownia, elektrociepłownia, blok upustowo-kondensacyjny, układ regeneracji*

1. INTRODUCTION

In order to optimise the power unit performance in combined heat and power plants it is required that efficiency of thermal cycles be improved. One of the key methods is applying the bled regeneration. The effectiveness of regeneration processes depends on the type of employed regeneration system and their operating parameters in the context of minimising the thermodynamic losses in regenerative heat exchangers. The thermodynamic losses in the regeneration systems are investigated in [1].

This study utilises the energy analysis of the extraction condensing type power unit in a combined heat and power plant with the high-pressure and low-pressure regeneration systems [2].

The power conversion efficiency of extraction condensing units in a combined heat and power plant approaches 33% in the range of optimal loads. Hence every attempt to introduce new solutions to improve the power conversion efficiency is justified and recommendable. Optimisation of the steam power plant performance can be achieved through improving the thermal efficiency of cycles of the power units.

The thermal efficiency of a unit can be increased through the control of main parameters of turbine, such as:

- temperature of the inlet steam t_1,
- pressure of the inlet steam p_1,
- pressure of the exit steam p_2.

These parameters are ordinarily predetermined by the manufacturer, already at the design stage and have to be maintained by the unit operator throughout the service life of the unit.

An increase of the average temperature of heat supply processes and an increase of average temperature of feed water to the boiler leads to an improvement of the thermal efficiency of the cycle. This effect might be achieved through the application of various solutions, including:

- in single contour cycles:
  - regenerative heating of feed water,
  - multistage superheating of steam,
- in multiple contour cycles:
  - application of gas and steam combined cycle systems.

The underlying principles of these solutions have been well known for long, yet they are still being developed and their practical applications are explored.

2. EFFECTIVENESS OF REGENERATION PROCESSES IN POWER UNIT

Underlying principles of the thermodynamic analysis of regeneration processes in a power plant are outlined in [3, 4], and certain errors have been put right. Analysed is a simple cycle of condensing unit in a steam power plant, complete with a three-stage bled regeneration system shown schematically in Figure 1. The process of regenerative preheating of feed water is achieved through the use of heat exchangers. In the analysed case these were the mixing heat exchangers XW1, XW2, XW3, the steam supplied from bleeds of a turbine. Depending on the number of heating stages, the feed water parameters might be improved in a greater or lesser degree. An increase of the feed water temperature directly affects the thermal efficiency of the cycle.

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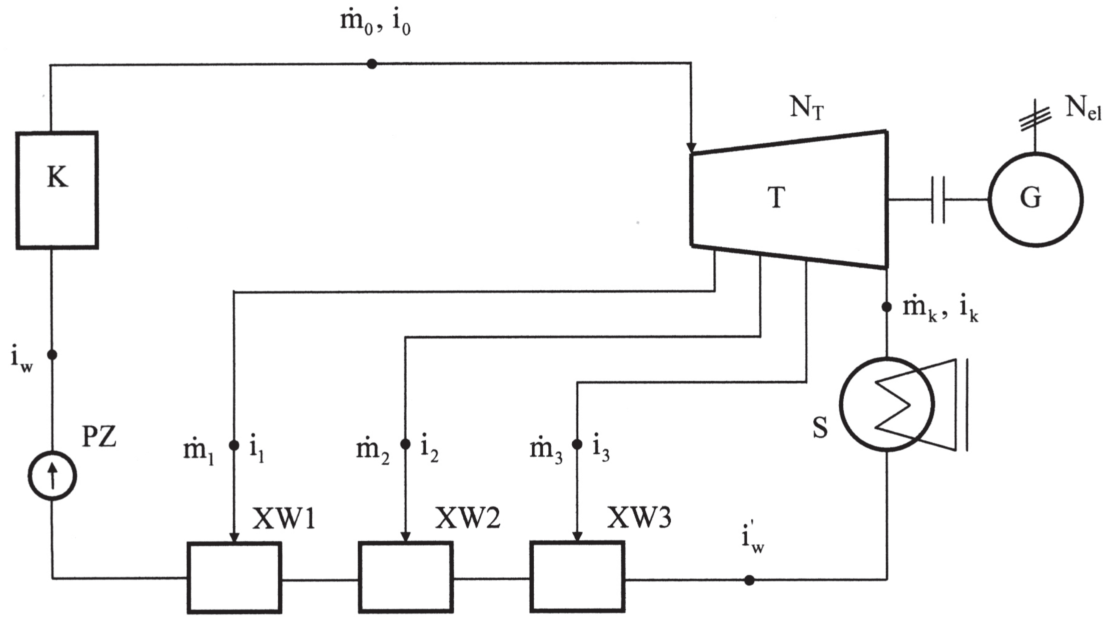

Fig. 1. Schematic diagram of a simple steam power plant unit installation with a three-stage regeneration system

Presented below is the analysis of a simple condensing unit, to illustrate the improvement of the thermal efficiency of the cycle with the bled regeneration with respect to that of the Clausius–Rankine cycle.

The thermal efficiency of a cycle with bled regeneration, shown schematically in Figure 1, is obtained from the formula

$$\eta_t^{(R)} = \frac{l_0}{q_d} \tag{1}$$

where:

l_0 – unit work of a cycle,
q_d – unit heat supplied to the cycle.

Unit work of the cycle is

$$l_0 = \frac{N_T}{\dot{m}_0} \tag{2}$$

The thermal power of the extraction condensing turbine is obtained from the formula

$$\begin{aligned} N_T &= m_1 \cdot (i_0 - i_1) + m_2 \cdot (i_0 - i_2) + \\ &+ m_3 \cdot (i_0 - i_3) + m_k \cdot (i_0 - i_k) \end{aligned} \tag{2a}$$

Taking into account the designations in Figure 1, we obtain the unit work of a cycle in the form

$$\begin{aligned} l_0 &= \frac{\dot{m}_1}{\dot{m}_0} \cdot (i_0 - i_1) + \frac{\dot{m}_2}{\dot{m}_0} \cdot (i_0 - i_2) + \\ &+ \frac{\dot{m}_3}{\dot{m}_0} \cdot (i_0 - i_3) + \frac{\dot{m}_k}{\dot{m}_0} \cdot (i_0 - i_k) \end{aligned} \tag{2b}$$

Introducing the mass fractions of the bleeds steam and steam supplied to the condenser, we get

$$\begin{aligned} l_0 &= \alpha_1 \cdot (i_0 - i_1) + \alpha_2 \cdot (i_0 - i_2) + \\ &+ \alpha_3 \cdot (i_0 - i_3) + \alpha_k \cdot (i_0 - i_k) \end{aligned} \tag{2c}$$

The unit work of a cycle is the sum of works generated in the turbine by the extraction steam $l_0^{(R)}$ and steam supplied to the condenser $l_0^{(K)}$

$$l_0 = l_0^{(R)} + l_0^{(K)} \tag{2d}$$

Hence:

$$l_0^{(R)} = \sum_{i=1}^{3} \alpha_i \cdot (i_0 - i_i) \tag{2e}$$

$$l_0^{(K)} = \alpha_k \cdot (i_0 - i_k) \tag{2d}$$

where:

$\alpha_i = \frac{\dot{m}_i}{\dot{m}_0}$ – mass fraction of bleed steam *i*,
i_i – specific enthalpy of bleed steam *i*,
$\alpha_k = \frac{\dot{m}_k}{\dot{m}_0}$ – mass fraction of steam supplied to the condenser.

The term expressing the thermal efficiency of a cycle with regeneration might be rewritten as

$$\eta_t^{(R)} = \frac{\frac{N_T}{\dot{m}_0}}{\frac{\dot{Q}_d}{\dot{m}_0}} = \frac{l_0}{q_d} = \frac{l_0}{i_0 - i_w} \tag{3}$$

In order to establish how the regeneration should impact on efficiency $\eta_t^{(R)}$, the relationship is sought between q_d and i_w and the fluxes of steam directed to the heat exchangers. Enthalpy of feed water to the boiler i_w and unit heat supplied to the medium in the boiler q_d is obtained from the formula:

$$i_w = \sum_{i=1}^{3} \alpha_i \cdot i_i + \alpha_k \cdot i'_w \tag{4}$$

$$q_d = \sum_{i=1}^{3} \alpha_i \cdot (i_0 - i_i) + \alpha_k \cdot \left(i_0 - i'_w\right) \tag{5}$$

Transforming Eq (3), we obtain

$$\eta_t^{(R)} = \frac{l_0^{(R)} + l_0^{(K)}}{l_0^{(R)} + \alpha_k \cdot \left(i_0 - i'_w\right)} \tag{3a}$$

It is evident that the difference $q_d^{(K)} = i_0 - i'_w$ is equal to unit heat supplied to the cycle with no regeneration system.

Thermal efficiency of this type of condensing cycle may be expressed as

$$\eta_t^{(K)} = \frac{l_0^{(K)}}{q_d^{(K)} \cdot \alpha_k} \tag{6}$$

Using Eq (6) enables us to transform Eq (3a), yielding

$$\eta_t^{(R)} = \eta_t^{(K)} \cdot \frac{1 + \xi_R}{1 + \eta_t^{(K)} \cdot \xi_R} \tag{7}$$

The ratio

$$\xi_R = \frac{l_0^{(R)}}{l_0^{(K)}} = \frac{\sum_{i=1}^{3} \alpha_i (i_0 - i_i)}{\alpha_k \cdot (i_0 - i_k)} \tag{8}$$

is a effectiveness indicator of a regeneration system for a unit termal cycle.

The formula (7) allows for evaluating thermodynamic effects achieved after introducing the regenerative preheating of feed water to the boiler in the units in power stations and combined heat and power plants. Practitioners tend to evaluate this effect basing on a relative increase of thermal efficiency of a cycle defined as the ratio of the difference of efficiency of a cycle with regeneration and that of the Clausius–Rankine cycle to the efficiency of the Clausius–Rankine cycle. Accordingly, we get

$$\Delta\eta_t^{(R)} = \frac{\eta_t^{(R)} - \eta_t^{(K)}}{\eta_t^{(K)}} \tag{9}$$

Taking Eq (7) into account, the relative increase of thermal efficiency of cycle with bled regeneration can be expressed as

$$\Delta\eta_t^{(R)} = \frac{(1 - \eta_t^{(K)}).\zeta_R}{1 + \eta_t^{(K)} \cdot \zeta_R} \tag{10}$$

It is evident in Eq (10) that the relative increase of efficiency $\Delta\eta_t^{(R)}$ will be always positive as long as $\zeta_R > 0$, the value of the increment $\Delta\eta_t^{(R)}$ increases with an increase of ζ_R and with the decrease of $\eta_t^{(K)}$. Similarly, a relationship is derived describing the thermodynamic effect of regeneration for more elaborate and complex installations.

In real installations the effectiveness of regeneration processes is affected by thermodynamic losses in the installation nodes. Major losses included in the loss balance are attributable to:

- inevitable difference in temperature of the thermofluids,
- limited number of heat exchangers for regeneration processes,
- imperfect distribution of bleeds steam condensed in the installation of regeneration system.

Reduced effectiveness of the regeneration process due to the above-mentioned losses negatively impacts on the thermal efficiency of the unit cycle. The values of relative increments of a cycle's thermal efficiency $\Delta\eta_t^{(R)}$ associated with the regeneration process depend to a large extent on the number of employed heat exchangers and parameters of incoming steam to the turbine. The influence of the number of regeneration stages on the increment of thermal efficiency, taking into account the increase in feed water temperature is shown for two different units:

1) a unit with a four-stage regeneration system (Fig. 2a),
2) with a ten-stage regeneration (Fig. 2b).

The parameters of fresh steam in these two units are summarised underneath. These illustrations are taken from [5].

The analysis of graphed relationships leads us to the following conclusions:

- for a given number of regeneration stages *n* the optimal thermal efficiency of a cycle and final temperature of feed water t_{wz} increases with an increase of fresh steam parameter values,
- as the number of regeneration stages increases, the increase of thermal efficiency in each subsequent stage tends to decrease, at the same time the costs of an extended installations become higher,
- in each case the thermal efficiency of a cycle reaches its optimal level for a precisely determined optimal temperature of feed water t_{wz} and this temperature rises with an increase in the number of regeneration stages *n*.

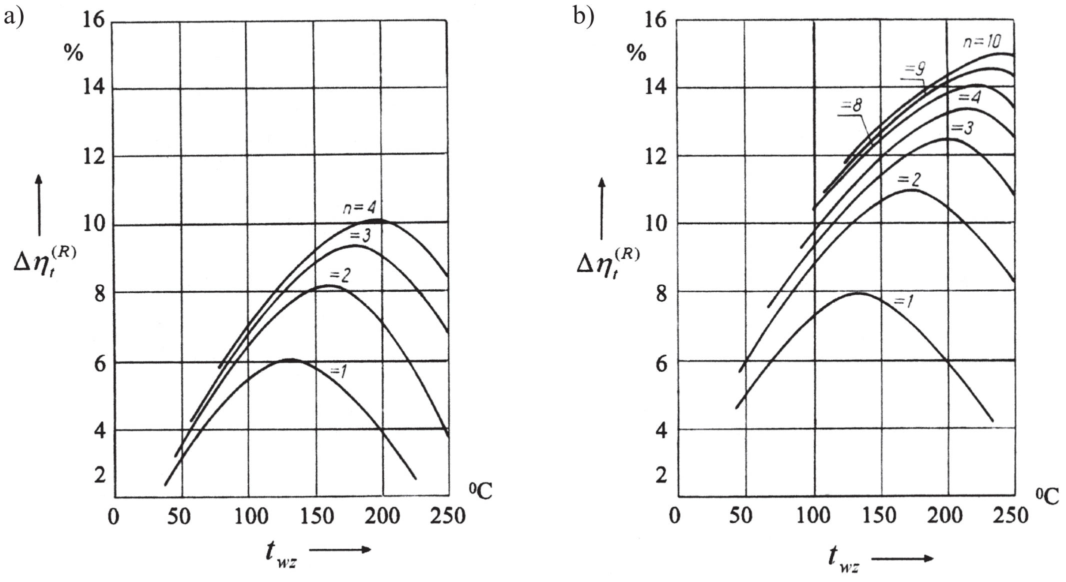

Fig. 2. Relative increase of thermal efficiency of a cycle $\Delta\eta_t^{(R)}$ in a steam power plant with bled regeneration system as the function of feed water temperature t_{wz} and the number of regeneration stages n: a) for a cycle with inlet steam parameters: p_1 = 3.5 MPa, t_1 = 435°C, n = 4; b) for a cycle with inlet steam parameters: p_1 = 13 MPa, t_1 = 535°C, n = 10

3. IDENTIFICATION OF CONTROL OBJECT

The combined heat and power plant "ECK Kraków S.A." has four power units and generates electricity and heat. The main purchaser of electric energy are energy distributing companies P.S.E and Z.E Kraków S.A. The main purchaser of heat is the company MPEC S.A.Kraków. The tested object was the extraction condensing type unit BC-90 no 2; one of the two extraction condensing type units in the plant.

The unit BC-90 has equipped with the following installations:

- coal-fines radiant drum boiler OP-380 type with secondary superheating steam;
- three-parts extraction condensing turbine 13UK125 type with heating bleeds; turbine sections: HP – high-pressure section, IP – intermediate-pressure section, LP – low-pressure section;
- heating exchanger system XA, XB;
- three-stage high-pressure regeneration system with heat exchangers: XW1, XW2, XW3;
- double-stage low-pressure regeneration system with the heat exchangers XN1, XN2;
- degasifier DG with a supply tank;
- feed pump PZ and condensate pump PK;
- synchronous generator TGH-120 with hydrogen – cooling system;
- generator transformer and a tap changing transformer;
- Hartmann und Braun control system.

Locations of all installations and their interconnections are shown in the flow chart in Figure 3.

BC-90 no 2 is a thermal power unit can be used for cogeneration of electricity and heat. Two operating modes are available:

1) heating working mode,
2) condensing working mode.

The main task of the combined heat and power plant is to meet the customers' demand for heat required for heating homes and industrial buildings in Kraków during the heating season. When the heating mode is selected, the heaters XA and XB have to be put in operation. In those conditions a condenser is supplied with minimal amounts of steam necessary to maintain the required thermal parameters of the final stages of the turbine.

The other available mode of operation is the condensing mode. When the demand for hot water for heating purposes is reduced during operation outside the heating season (in the summertime) the power unit is switched to the condensing mode of operation and generates only the required amount of electricity whilst the steam admission from district heating bleeds V and VI to heating exchangers XA and XB is entirely cut off (Fig. 3).

The operation of the power unit involves all parts of turbine whilst district heating bleeds can be either shut or support two low-pressure feed water heaters XN1 and XN2. The steam rate from the low-pressure section of turbine in the condensing mode accounts for 6–7% of flow amount in the heating mode. Steam utilised by the turbine passes to the condenser, yet its enthalpy is then higher than in the heating mode of operation. The stream of condensing steam reaching the condenser is 3÷4 times greater than the steam flux in the heating mode. The condenser operates under heavy work loads hence the need for effective use of cooling towers to supply the cooling water to the condenser and transfer the useless condensation heat of steam to the atmosphere. Gross heat consumption by the unit exceeds 10 MJ/kWh.

The thermal power generation unit BC-90 was the object of the power analysis as a part of the research program outlined in the introductory section.

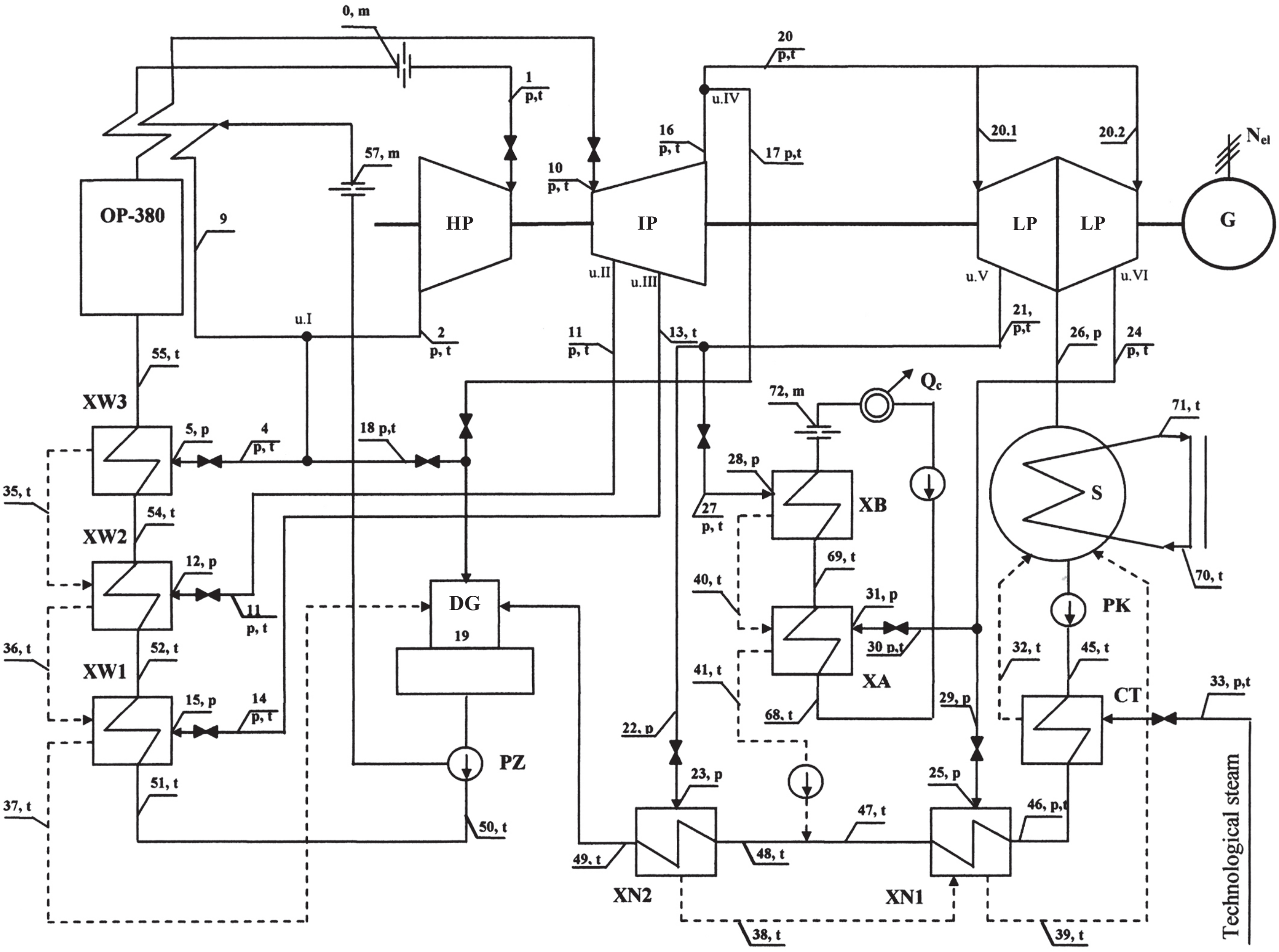

Fig. 3. Balance scheme of the BC-90 type power unit with measurement points distribution

4. PERFORMANCE PARAMETERS FOR A POWER UNIT BC-90

The measurements were taken for the power unit with the regeneration system:

- in the heating mode of operation: for nine states under the loads in the range of 72.25÷107.72 MW,
- in the condensing mode of operation: for nine states under the loads from the range 75.20÷114.20 MW.

Steam expansion process in a turbine for the condensing and heating mode of operation for the given optimal loads are shown in Figures 4 and 5.

Measurement data were further utilised to formulate the balance of a thermal cycle for the investigated unit. Characteristic parameters of unit operation were found:

- gross (11) and net (11a) power conversion efficiency of the unit defined as the efficiency of electric energy generation in an unit

$$\eta_{EK}^{(b)} = \frac{N_{el}}{m_p . W_d} \tag{11}$$

$$\eta_{EK}^{(n)} = \frac{N_{el} - N_{pwb}}{m_p . W_d} \tag{11a}$$

where:

N_{el} – electric power on the generator terminals,
N_{pwb} – auxiliary power for the unit,
m_p – consumption of fuel with a calorific value W_d.

For the heating mode of operation were calculated:

- cogeneration factors:
  - overall cogeneration factor

$$\sigma_o = \frac{N_{el}}{Q_c} \tag{12}$$

  - counter-pressure cogeneration factor

$$\sigma_p = \frac{N_{el_p}}{Q_c} \tag{13}$$

where:

N_{el_p} – electric power generated by the counter pressure part of the turbine,
Q_c – thermal power generated by the unit;

- values of the fuel chemical energy conversion factor for the extraction condensing unit

$$\xi_{UK} = \eta_k \, \eta_{EK}^{(b)} \frac{\sigma_0 + 1}{(\sigma_p + 1) \cdot \eta_{EK}^{(b)} + (\sigma_0 - \sigma_p)\eta_k} \tag{14}$$

where η_k stands for boiler efficiency.

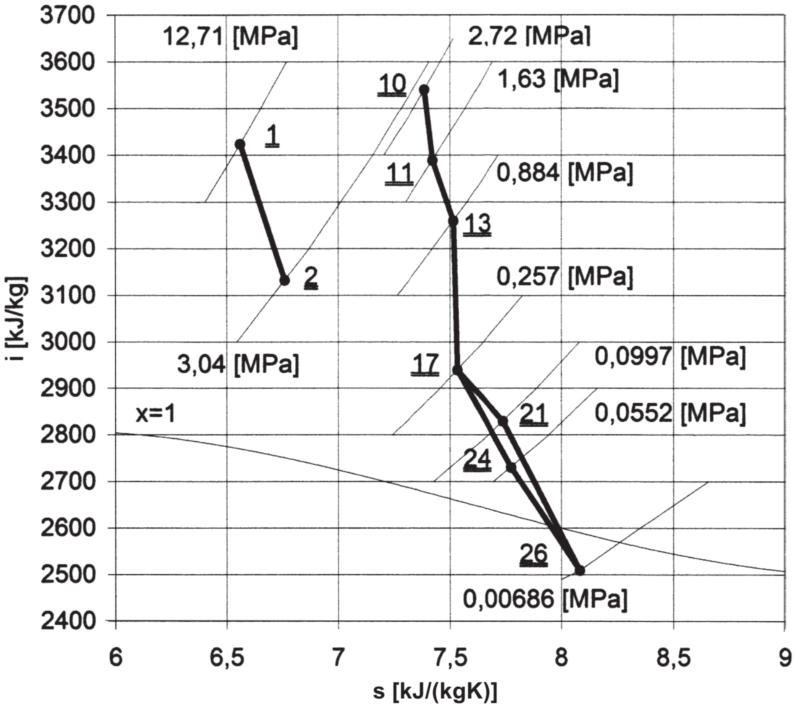

Fig. 4. Diagram of the steam expansion in a turbine for $N_{el} = 106.48$ MW – heating working mode

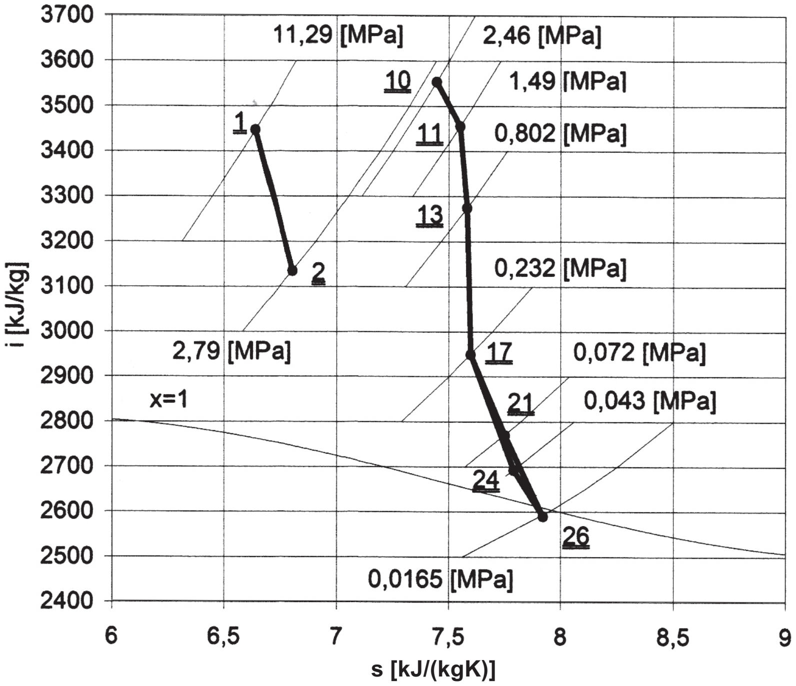

Fig. 5. Diagram of steam expansion in a turbine for $N_{el} = 109.10$ MW – condensing working mode

Measurement data supported by a calculation program written by the author were utilised to formulate the energy balance for the whole unit and to plot the unit performance characteristics.

5. CONCLUSIONS

The experimental program allowed for computing the energy balance and to give a graphic representation of the performance parameters of the unit under the operating loads.

The key parameters of the unit performance are: power conversion efficiency and thermal factors. The power conversion efficiency profile suggests that the work load can be selected such that the efficiency reach its maximal value. This load is referred to as "economy load". Power conversion efficiency profiles enable the unit operator to select the optimal loading range. It is evident that when operating the unit under loads to the right from the "economy load" operating point an increased load should not lead to an improved efficiency. The power conversion efficiency profile for the operating load range in the heating mode of operation is shown in Figure 6, for the condensing mode – in Figure 8.

These characteristic reveal that:

- in the condensing mode of operation the maximal efficiency of the unit approaches $\eta_{EK}^{(b)} = 33.02\%$ under the load $N_{el} = 109.1$ MW,
- in the heating mode of operation the maximal efficiency of the unit will be $\eta_{EK}^{(b)} = 30.78\%$ under the load $N_{el} = 106.48$ MW.

The ratio as quotient of sum of generated electric power and thermal power generated by unit both in the heating and condensing mode to the thermal power of fuel is expressed as the fuel chemical energy conversion factor ξ_{UK} for the unit. Depending on the working mode, the values of this factor vary. In the heating mode of operation this factor given information about the effective utilisation of chemical energy of the fuel in electric energy and heat in cogeneration process. As regards the condensing mode, the factor ξ_{UK} assumes the value of the gross power conversion efficiency of the unit $\eta_{EK}^{(b)}$, which becomes readily apparent when characteristics in Figures 8 and 9 are compared. In this operating mode the amount of produced heat in relation to electric energy is negligibly small, as the demand for space heating is low in summer months (outside heating season). Large amounts of heat from condensation processes are released to the surroundings through the cooling water cycle in cooling towers.

Other indicators applicable to the heating working mode of extraction condensing unit include:

- overall cogeneration factor σ_o,
- counter-pressure cogeneration factor σ_p.

The overall cogeneration factor so expresses the amount of generated electric power N_{el} in relation to the amount of produced thermal power Q_c. The counter pressure cogeneration factor σ_p expresses the amount of electric energy produced by steam in the counter-pressure part to that of heat produced by unit for heating purposes. The profiles of these two factors for a extraction condensing unit operating in the heating mode are given in Figure 7.

For economical load N_{el} =109.1 MW in the condensing working mode the fuel chemical energy conversion factor approaches the value ξ_{UK} = 0.330. In the heating working mode of operation and for the economical load N_{el} =106.48 MW the values of these factors are:

- the fuel chemical energy conversion factor for the extraction condensing type power unit ξ_{UK} = 0.761,
- the overall cogeneration factor σ_o = 0.679,
- the counter pressure cogeneration factor σ_p = 0.0624.

The evaluation of BC-90 unit performance in the combined heat and power plant is a preliminary stage for the assessment of thermodynamic losses in the regeneration systems, which is outlined in [2].

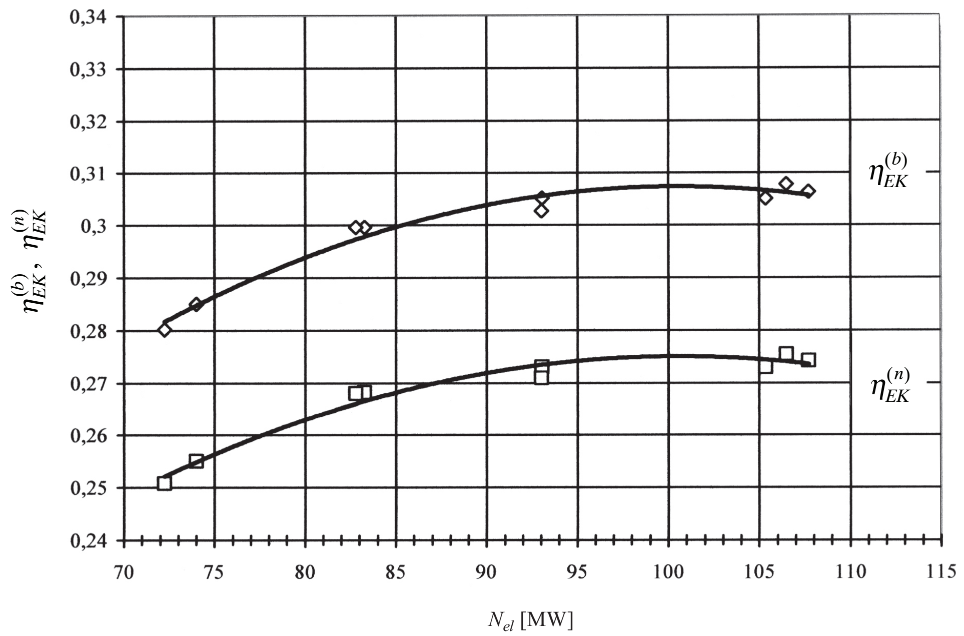

Fig. 6. Characteristics of power conversion efficiency of a extraction condensing unit type for a heating working mode

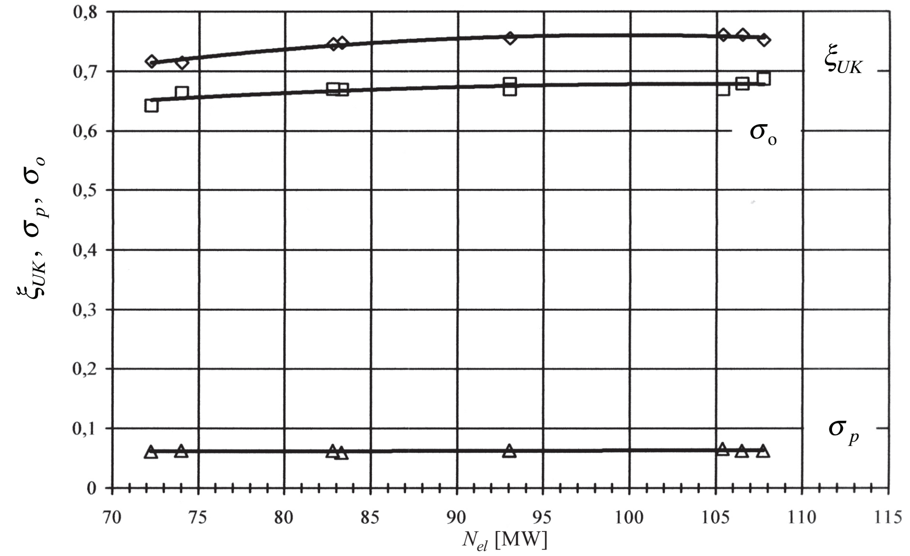

Fig. 7. Characteristics of thermal indicators of a extraction condensing unit type for heating working mode

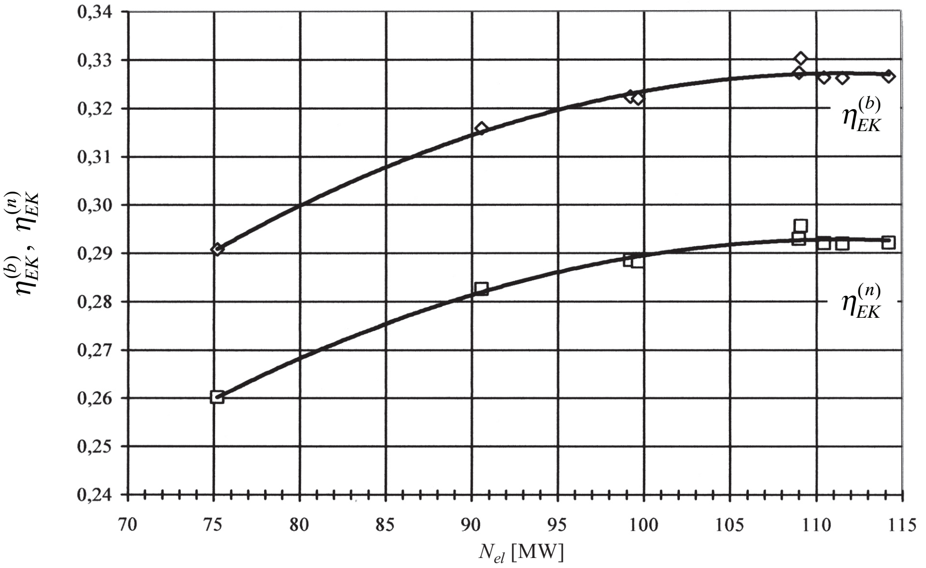

Fig. 8. Characteristics of power conversion efficiency of a extraction condensing unit type for a condensing working mode

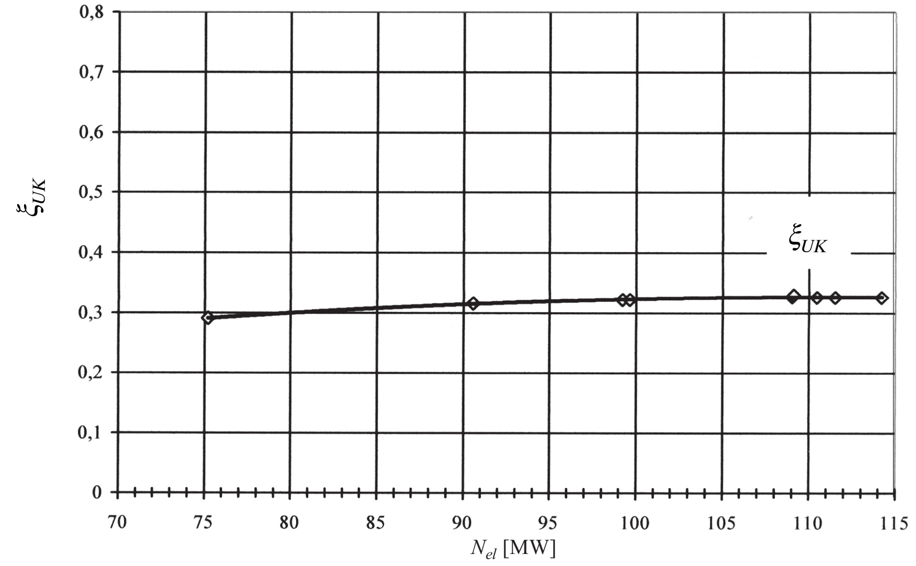

Fig. 9. Fuel chemical energy conversion factor for a extraction condensing unit for a condensing working mode

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