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ANALYSIS OF THE THERMODYNAMIC LOSSES IN THE REGENERATION SYSTEM OF THE EXTRACTION CONDENSING TYPE POWER UNIT AT A COMBINED HEAT AND POWER PLANT

SUMMARY

The paper outlines the method of evaluating thermodynamic losses in the regeneration systems of the extraction condensing type power unit in a combined heat and power plant.
The exergy analysis principles were then utilised to compute the thermodynamic losses in heat exchangers of the high-pressure regeneration system in the heating and condensing mode of power unit operation. Finally, the thermodynamic losses are expressed in terms of increased fuel consumption in the boiler, which is of key importance for the calculations of overall costs of power and heat generation in a combined heat and power plant.

***Keywords**: combined heat and power plant, extraction condensing type power unit, regeneration system, thermodynamic losses, exergy analysis*

ANALIZA STRAT TERMODYNAMICZNYCH W UKŁADACH REGENERACJI BLOKU UPUSTOWO-KONDENSACYJNEGO ELEKTROCIEPŁOWNI

W artykule przedstawiono metodykę obliczenia strat termodynamicznych w układach regeneracji bloku upustowo-kondensacynego. Następnie w oparciu o zasady analizy egzergetycznej wyznaczono wartości strat termodynamicznych w wymiennikach regeneracji wysokoprężnej zarówno dla ciepłowniczego, jak i kondensacyjnego trybu pracy bloku. W części końcowej opracowania przeliczono wartości tych strat na koszty nadmiernego zużycia paliwa dostarczonego do kotła, które stanowią istotną pozycję w ogólnych kosztach produkcji energii elektrycznej i ciepła w elektrociepłowni.

***Słowa kluczowe**: elektrociepłownia, blok upustowo-kondensacyjny, układ regeneracji, straty termodynamiczne, analiza egzergetyczna*

1. INTRODUCTION

Bled regeneration is the fundamental method of optimisation of a steam power plant performance. Underlying this method is the power engineering analysis outlined in [1]. To improve the effeectiveness of regeneration it is required that the thermodynamic losses in the regeneration systems in a power plant or a combined heat and power plant be minimised. This paper focuses on thermodynamic losses in the regeneration systems of a extraction condensing power unit in a combined heat and power plant.

In the preliminary stage of the research program thermal measurements were taken of the BC-90 unit under a wide range of operating loads, both in the heating and condensing mode of operation. Measurement data were then utilised to formulate the algorithm for the energy balance of a unit and to do the required calculations. The exergy analysis methods were applied to find the thermodynamic losses in the heat exchangers of the regeneration system. A qualitative and quantitative analysis of the thermodynamic losses were performed. Detailed results are given elsewhere [2].

2. METHODOLOGY OF DETERMINING THERMODYNAMIC LOSSES

Any real heating process involves unrecoverable exergy losses. Each exergy loss leads to an increase of energy supplied to the process or to a reduction of thermal effects. An exergy loss flux δ_q associated with irreversibility of processes inside the control volume is derived from the Gouy–Stodola law

$$\delta_q = T_{ot} \cdot \sum_i \Delta \dot{S}_i \tag{1}$$

where:

$\sum_i \Delta \dot{S}_i$ – sum of entropy flux increments of i-bodies involved in the process,

T_{ot} – ambient absolute temperature.

Heat transfer is one of the most frequently encountered phenomena responsible to a large extent for irreversibility of thermal processes. In accordance with the exergy analysis principles outlined in [3, 4, 5], an exergy loss flux in an analysed heat exchanger k (in a unit of time) due to an irreversible heat transfer between steam and water (media whose mean temperatures can be in steady state), is given by the formula

$$\delta_{q_k} = T_{ot} \cdot \left(\frac{\dot{Q}_w}{\bar{T}_w} - \frac{\dot{Q}_p}{\bar{T}_p} \right) \tag{2}$$

where:

$\bar{T}_w = \frac{T_1 + T_2}{2}$ – average absolute temperature of water,

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$\bar{T}_p = \dfrac{i_a - i_b}{s_a - s_b}$ – average absolute temperature of steam,

i – specific enthalpy,

s – specific entropy,

$\dot{Q}_w = q_w \cdot \dot{m}_w$ – thermal power of heated feed water,

$\dot{m}_w$ – feed water mass flux,

$\dot{Q}_p = q_p \cdot \dot{m}_{p^\times}$ – thermal power of steam supplying the heat exchanger,

$\dot{m}_{p^\times}$ – mass flux of steam,

$q_w = i_2 - i_1$ – unit heat of feed water,

$q_p = i_a - i_b$ – unit heat of steam,

$\Delta\dot{S}_w = \dfrac{\dot{Q}_w}{\bar{T}_w}$ – increment of feed water entropy flux,

$\Delta\dot{S}_p = \dfrac{\dot{Q}_p}{\bar{T}_p}$ – increment of entropy flux of steam supplying the heat exchanger.

Designations, nomenclature and the methodology of determining thermodynamic losses in typical heat exchangers in regeneration systems are given in Figure 1. When a regeneration system comprises k heat exchangers, the exergy loss flux for the whole system is derived from the formula

$$\delta_q = \sum_k \delta_{q_k} \tag{2a}$$

When thermal power of incoming steam to the turbine N_T is constant, thermodynamic loss in the regeneration system brings about power fluctuations on the generator terminals. In accordance with relationships given in [5], this power change is expressed as

$$\Delta N_{el} = -\left(\delta_q - N_T \cdot \delta\eta_i\right) \cdot \eta_g \tag{3}$$

Assuming that the internal efficiency of turbine η_i remains unchanged, this relationship might be expressed in a simpler form

$$\Delta N_{el} = -\delta_q \cdot \eta_g \tag{3a}$$

where η_g – generator efficiency.

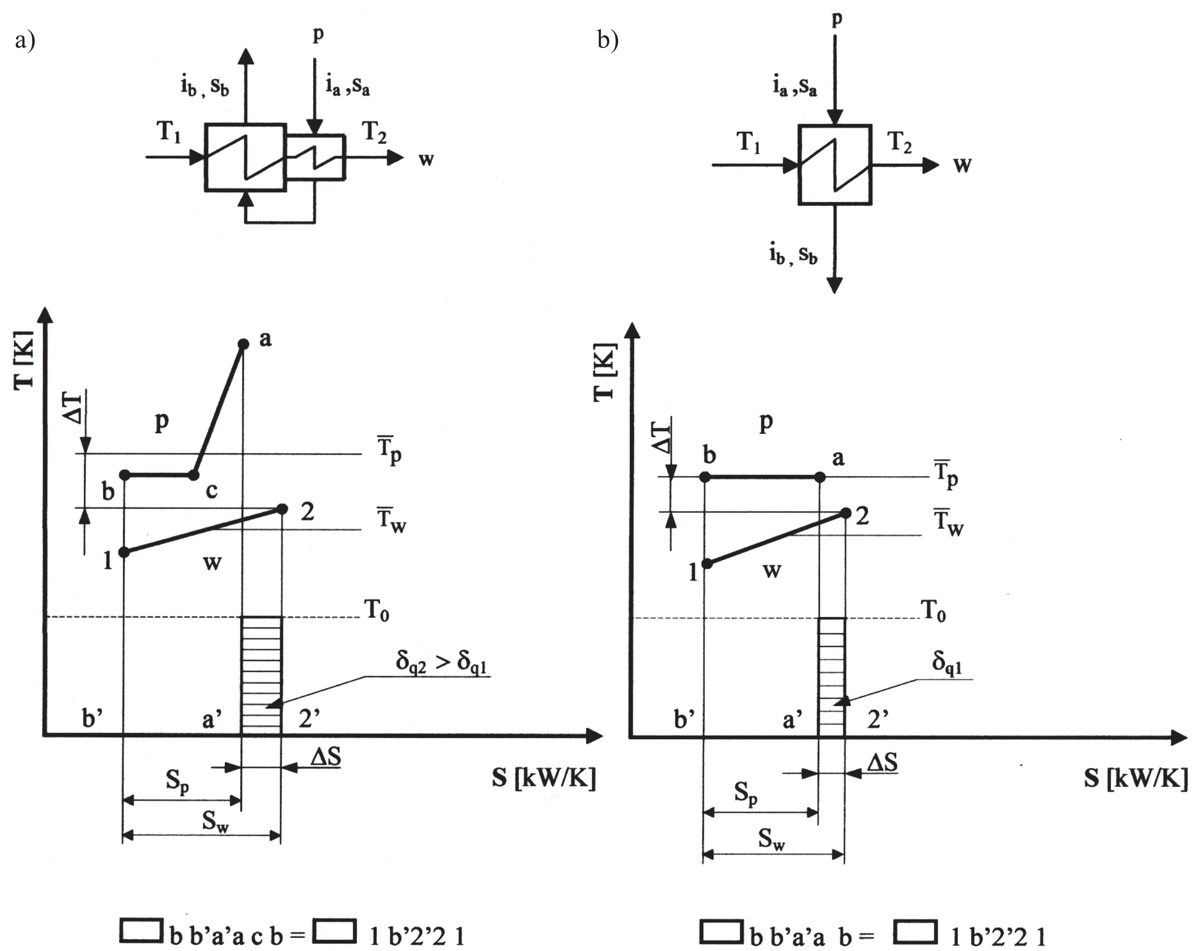

Fig. 1. Thermodynamic losses: a) in a two-section heat exchanger supplied by superheated steam; b) in a single-section heat exchanger supplied by saturated steam

The power difference due to thermodynamic losses produces a change in the heat consumption by the unit Δq_b, which is given by (4) after putting right the errors mentioned in [6]. Accordingly, we get

$$\Delta q_b = \frac{\dot{m}_p \cdot W_d}{N_{el} + \Delta N_{el}} - \frac{\dot{m}_p \cdot W_d}{N_{el}} = -q_b \frac{\Delta N_{el}}{N_{el} + \Delta N_{el}} \qquad (4)$$

where:

$\dot{m}_p$ – fuel consumption in a boiler,

W_d – calorific value of the fuel,

$q_b = \dfrac{\dot{m}_p \cdot W_d}{N_{el}}$ – unit heat consumption in the power unit.

The value of thermodynamic losses depends on the actual configuration of the power installation and the parameters of the working medium. Results gathered so far suggest that minimisation of these losses is of more importance than searching for the optimal feed water temperature difference in the heaters [7, 8]. This statement is justified particularly in the case of power units complete with secondary superheating steam and extended high-pressure regeneration systems.

3. IDENTIFICATION OF THE INVESTIGATION 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 is 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 parts: HP – high-pressure, IP intermediate-pressure, LP low-pressure;
- three-stage high-pressure regeneration system with heat exchangers: XW1, XW2, XW3;
- double-stage low-pressure regeneration system with the heat exchangers XN1, XN2;
- heating exchangers system XA, XB;
- 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 2.

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.

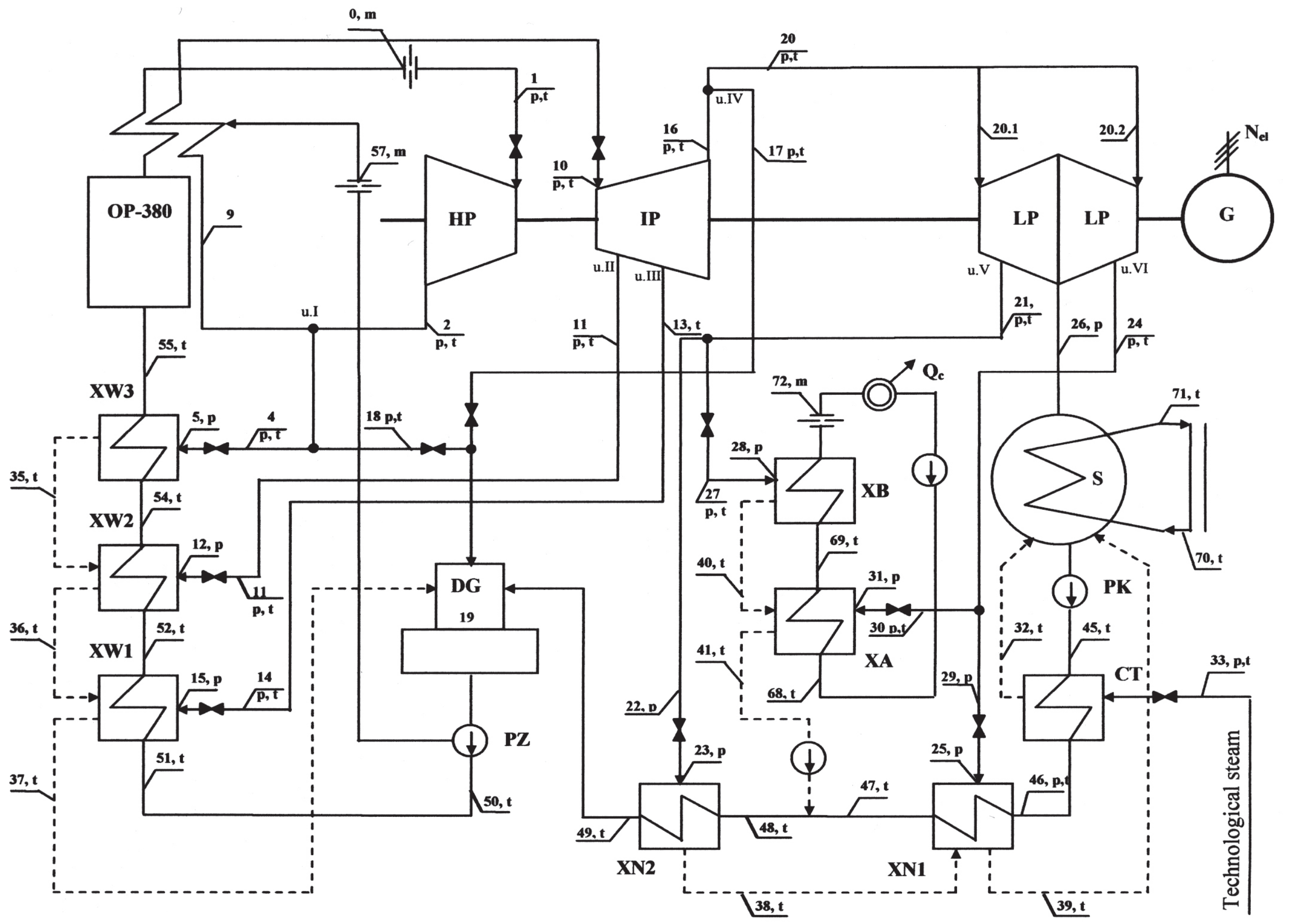

Fig. 2. Extraction condensing type unit BC-90 in the combined heat and power plant ECK S.A. – schematic flow diagram with measurement points distribution

The main task of the thermal power plant is to meet the customers' demand for heat required for space heating in Kraków during the heating season. When the heating mode is selected, the water heaters XA and XB, supplied by steam from district heating bleeds V and VI, are 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 mode of BC-90 operation is the condensing mode. When the demand for hot water for heating purposes is reduced (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 heat exchangers XA and XB is partly or wholly cut off (Fig. 2). The operation of the power unit involves all turbine components whilst district heating bleeds can be either shut or support two low-pressure feed water heaters XN1 and XN2. The steam flux from the low-pressure section LP in the condensing mode accounts for 6÷7% of flow 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 flux 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 releases the useless heat of condensation to the atmosphere. Gross heat consumption by the unit exceeds 10 MJ/kWh.

Regeneration system in the power unit BC-90 comprises the low-pressure system (XN), a variable pressure degasifier DG and high-pressure regeneration system (XW). Low-pressure regeneration involves two low-pressure heaters: XN1, XN2. Condensed steam from the low-pressure regeneration passes to the condenser. The high-pressure regeneration system comprises three high-pressure heat exchangers XW1, XW2, XW3 (Fig. 2).

These are diaphragm-type water-steam exchangers: U-sections, vertical, 3-phase surface exchangers. Heat exchangers are supplied with heated steam with high parameters from the following discharges in the turbine generator set:

– from bleed I in the high-pressure part HP of the turbine set 13UK125 steam is supplied to the heat exchanger XW3,
– from bleed II in the intermediate-pressure part IP of the turbine set steam is supplied to the heat exchanger XW2,
– from bleed III in the intermediate-pressure part IP of the turbine set steam is supplied to the heat exchanger XW1.

Feed water to the boiler OP-380 passes through the regeneration system.

4. THERMODYNAMIC LOSSES IN THE HIGH-PRESSURE REGENERATION SYSTEM

Measurement data supported by a program written in Microsoft Excel by the author were utilised to formulate the energy balance for the whole unit and to plot the unit performance characteristics. Results of the research program were utilised in the analysis of thermodynamic losses in the regeneration systems for the BC-90 unit.

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

– in the heating mode of operation: for nine states under the loads from the range N_{el} =72.25÷107.72 MW,
– in the condensing woking mode: for nine states under the loads from the range N_{el} =75.20÷114.20 MW.

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 parameter of the unit performance is its power conversion efficiency. The power conversion efficiency profile suggests that the unit load can be selected such that the efficiency reach its maximal value. This load is referred to as “economy load”. This load level is recommended while the power unit is in service, at the same time it might serve as the baseline data for computing thermodynamic losses in the present study. Of particular interest is the high-pressure regeneration system as the temperature difference between the working media in the heaters is significant. A large temperature difference ΔT between the media is the consequence of parameters of steam supplying the heat exchanger XW. Thermodynamic losses in high-pressure regeneration system of the extraction condensing type unit are obtained for the heating and condensing mode of operation. In order to find thermodynamic losses in the high-pressure regeneration system, characteristic parameters of the unit performance under the investigated work load range have to be established:

– temperature difference ΔT between the media in particular heat exchangers,
– power change ΔN_{el} across the generator terminals,
– difference in heat consumption for the unit Δq_{b},
– difference in fuel consumption Δm_p,
– fraction of annual cost of fuel consumption K_R.

Control of parameters ΔN_{el}, Δq_b, Δm_p, K_R is associated with the occurrence of thermodynamic losses in the high-pressure regeneration system. They are plotted in the function of work load for the two modes of power unit operation. These characteristics were particularly useful in the analysis of thermodynamic losses. Thermodynamic losses in a low-pressure regeneration system (exchangers XN1, XN2) are not considered as they are negligible in relation to those occurring in high-pressure regeneration system.

4.1. Condensing working mode

Thermodynamic losses in relation to the ambient conditions are shown in *T-s* profiles in Figures 3–5, for heat exchangers XW1, XW2, XW3 under the economy load of power unit operating in a condensing mode. It is readily apparent that for economy load N_{el} = 109.10 MW the losses in exchangers XW2, XW1 account for a large proportion of the total thermodynamic loss. The loss δ_q in the heat exchanger XW3 is represented by the smallest area, which is associated with lower enthalpy of steam supplying this exchanger.

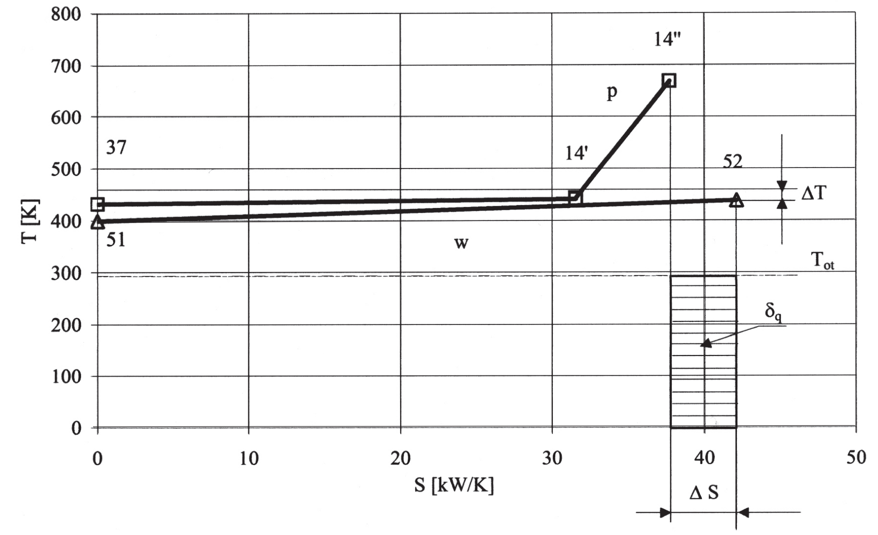

Fig. 3. Exergy loss δ_q in the exchanger XW1 for economy load N_{el} =109.1 MW in the condensing mode of operation

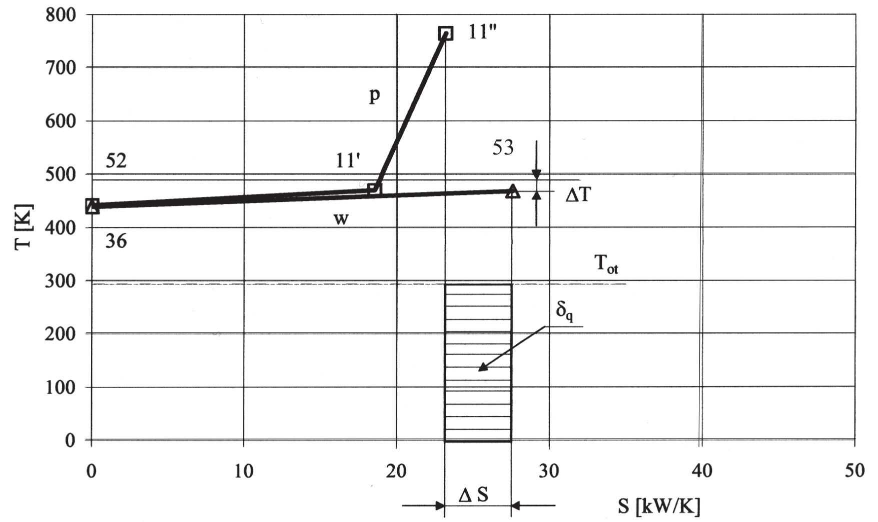

Fig. 4. Exergy loss δ_q in the exchanger XW2 for economy load N_{el} =109.1 MW in the condensing mode of operation

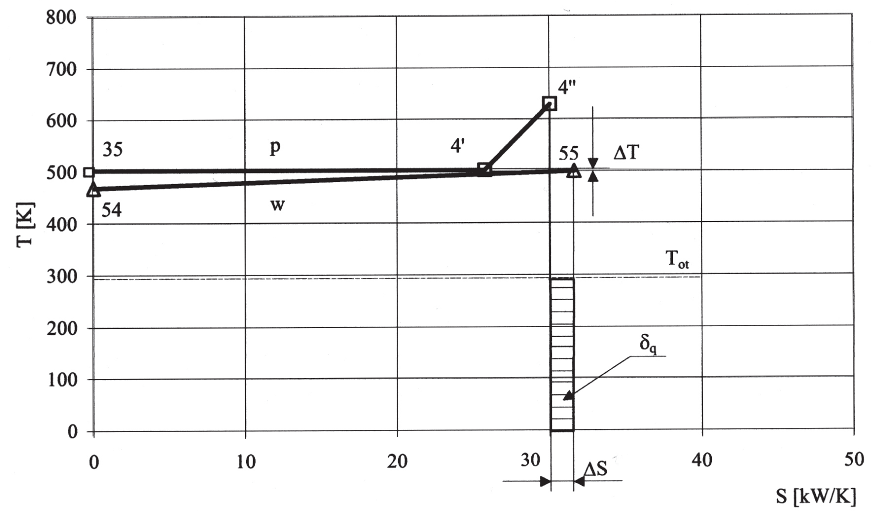

Fig. 5. Exergy loss δ_q in the exchanger XW3 for economy load N_{el} =109.1 MW in the condensing mode of operation

The temperature difference ΔT between the media involved in the heat transfer is of major importance. It means that thermodynamic losses increase in proportion with an increase in temperature difference ΔT. The values of parameter ΔT for particular heaters XW in the investigated operating load range are shown in Figure 6.

The largest values of ΔN_{el} are registered in the exchanger XW2 as thermodynamic losses there prove to be the largest. Power fluctuations on the generator terminals shall lead to variations in fuel consumption in the power unit Δm_p. Heat consumption profiles q_b in the operating load range for the high-pressure heaters XW1, XW2, XW3 are shown in Figure 8.

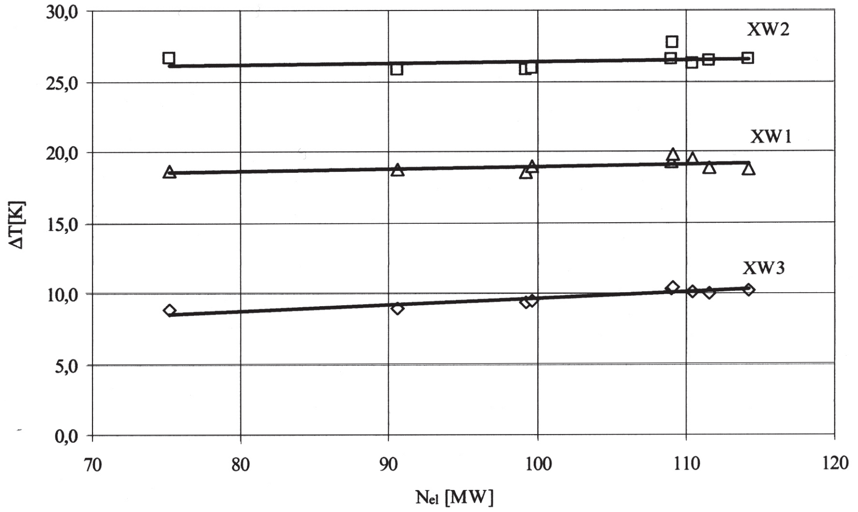

Fig. 6. Temperature difference ΔT between the media in heaters in the range of operating loads in the condensing mode of operation

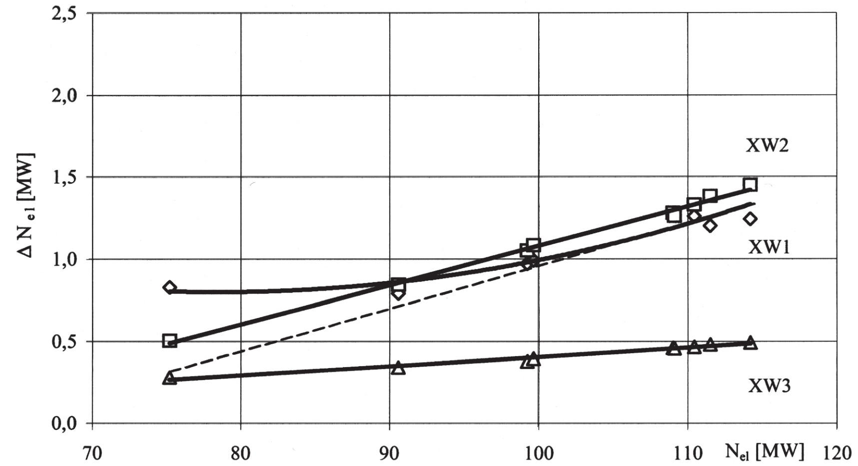

Fig. 7. Fluctuations of electric power ΔN_{el} for the condensing mode of operation

The largest temperature difference between the media (steam, water) are registered in the heat exchanger XW2, in XW1 are average values of ΔT. Temperature difference in XW3 proves to be the smallest. For the economy load N_{el} = 109.10 MW and the condensing mode of operation its values are:

- ΔT = 19.6 K for heater XW1,
- ΔT = 27.7 K for heater XW2,
- ΔT = 10.4 K for heater XW3.

The power difference ΔN_{el}, difference in heat consumption in the power unit Δq_b and consequently the variations in fuel consumption Δm_p are plotted in the function of work load in Figures 7–9. The power drop on the generator terminals due to the heat transfer to the surroundings in the operating load range follows a linear pattern. As work load increases, the power difference ΔN_{el} in heaters tends to rise (Fig. 7).

The plot of heat consumption q_b, by the extraction condensing type unit in the operating load range is shown in Figure 10. The minimal value q_b, is achieved for economy load in the condensing mode of operation. Fluctuations of heat consumption Δq_b, by the power unit might be expressed in terms of fluctuations of fuel consumption Δm_p. Figure 9 shows fluctuations of fuel consumption in the function of work load. The characteristics obtained for the exchangers XW1 and XW3 are linear. In the case of XW2 in the range below 100 MW the characteristic deviates from the linear. These nonlinearities might be attributable to measurement errors because similar characteristics obtained for the heating mode are linear for all investigated heat exchangers. It is reasonable to suppose that correct profiles of ΔN_{el}, Δq_b, Δm_p for the exchanger XW2 in the loading range below 100 MW are represented by dashed lines in Figures 7–9.

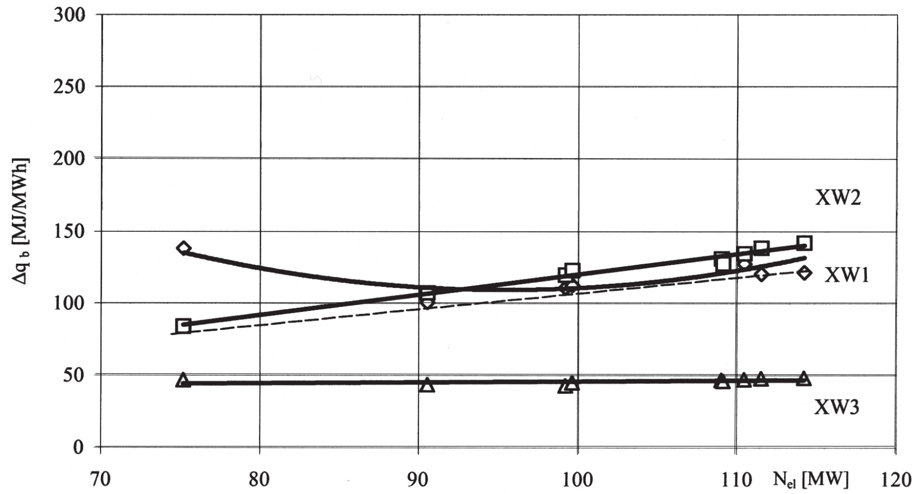

Fig. 8. Fluctuations of heat consumption in the block Δq_b for the condensing mode of operation

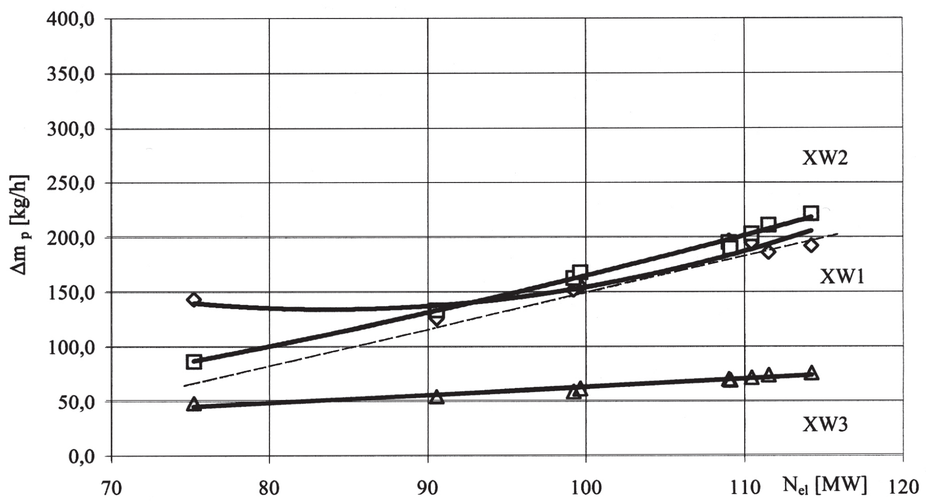

Fig. 9. Fluctuations of fuel consumption in the unit Δm_p for the condensing mode of operation

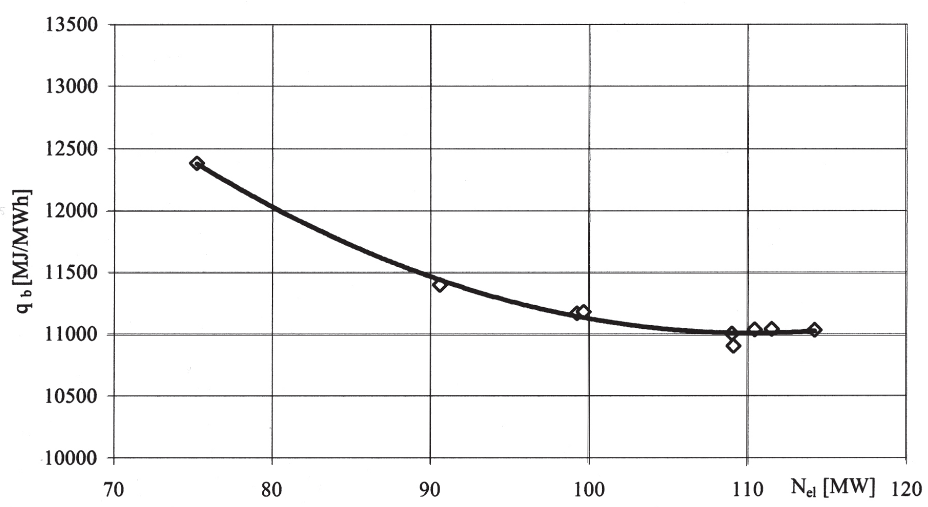

Fig. 10. Heat consumption in the unit q_b for the condensing mode of operation

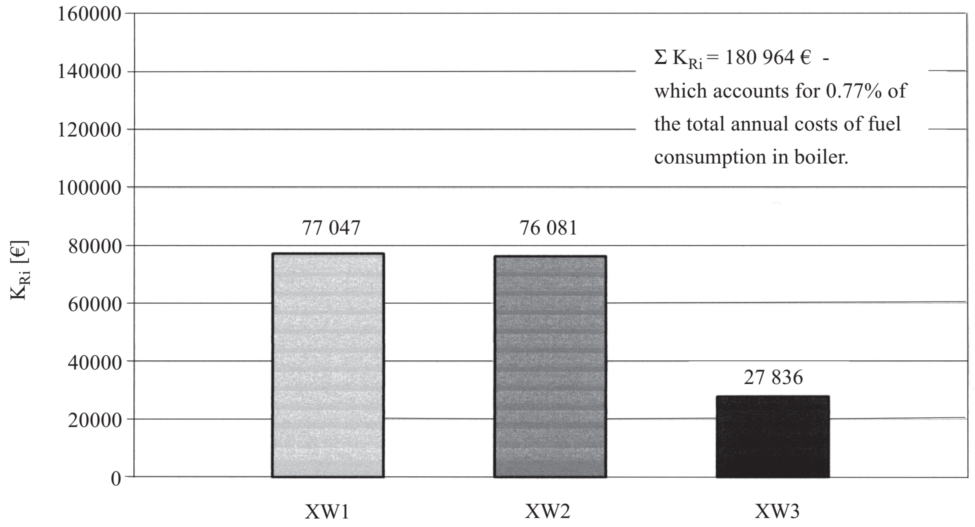

Fig. 11. Annual costs due to excessive fuel consumption K_{Ri} caused by thermodynamic losses in the high-pressure regeneration system for the economy load N_{el} = 109.1 MW – condensing working mode

The costs of power generation in the combined heat and power plant ECK S.A. increase with an increase in thermodynamic losses in the regeneration system. The amount of fuel used in a boiler for the economy load N_{el} = 109.1 MW is equal to m_p = 59 179 kg/h. The fraction of fuel loss in the condensing mode is about $\sum\Delta m_p$ = 452 kg/h, which accounts for 0.77% of total fuel consumption in a boiler. The annual costs of fuel loss for the exchangers XW1, XW2 and XW3 are shown in Figure 11. In the condensing mode of operation the sum total of annual costs of fuel loss due to existing thermodynamic losses in the high-pressure regeneration system in the extraction condensing power unit approach ΣK_R = 180 964 €.

4.2. Heating working mode

Similarly as for condensing mode of operation, thermodynamic losses for the heating mode of operation are presented in the form of *T–s* diagrams and work load profiles. *T–s* diagrams were graphed for each heater in the high-pressure regeneration system for the economy load equal to N_{el} = 106.48 MW (Figs 12–14).

It is evident that the representative area of exergy loss flux for the exchanger XW2 is much larger in the heating mode (Fig. 13) than in the condensing mode of operation (Fig. 4). Variations of electric power N_{el}, of heat consumption Δq_b, and, consequently, fuel consumption Δm_p in the range of operating loads are shown on plots in Figures 16–18.

Variations of temperature difference ΔT between the heat exchanging agents in high-pressure regeneration heaters: XW1, XW2, XW3 are given as work load profiles in Figure 15.

The temperature difference ΔT in XW1 is the largest, as it was the case in the condensing mode of operation, too.

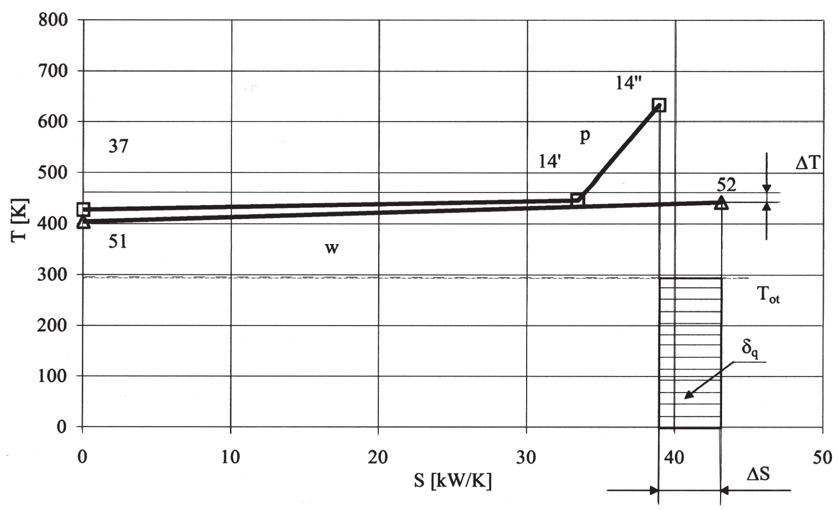

Fig. 12. Exergy loss δ_q in the exchanger XW1 for economy load N_{el} = 106.48 MW in the heating mode of operation

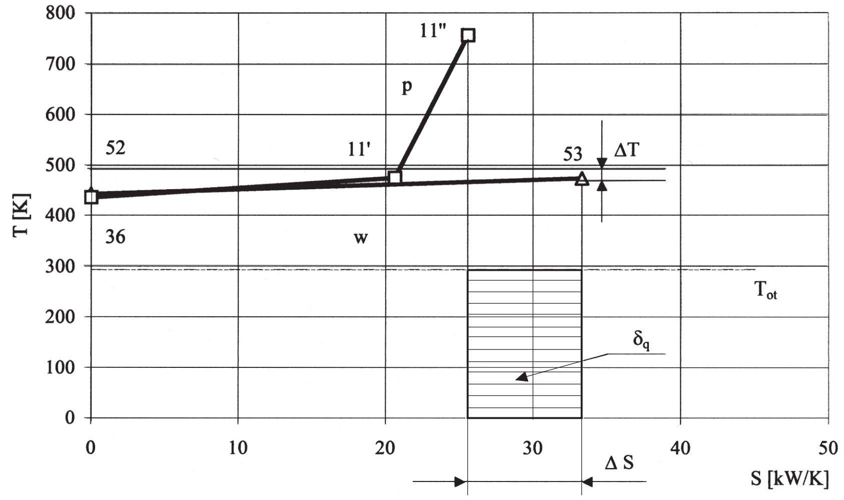

Fig. 13. Exergy loss δ_q in the exchanger XW2 for economy load N_{el} = 106.48 MW in the heating mode of operation

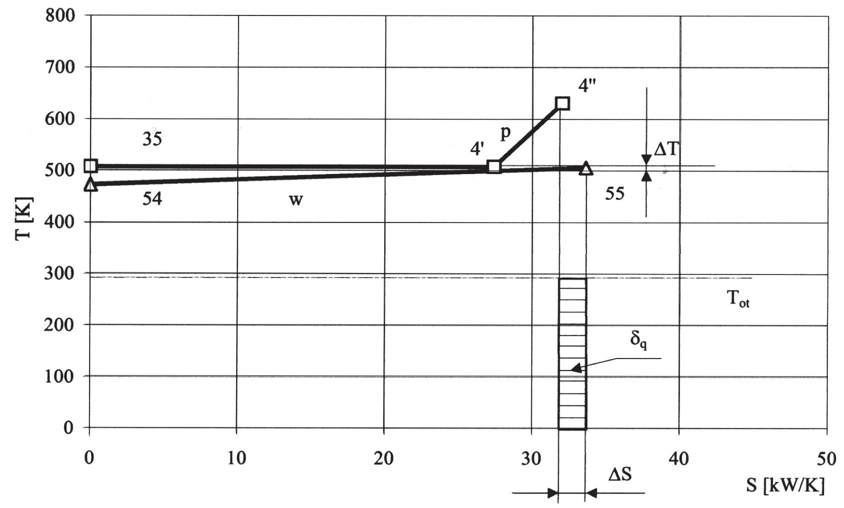

Fig. 14. Exergy loss δ_q in the exchanger XW3 for economy load N_{el} = 106.48 MW in the heating mode of operation

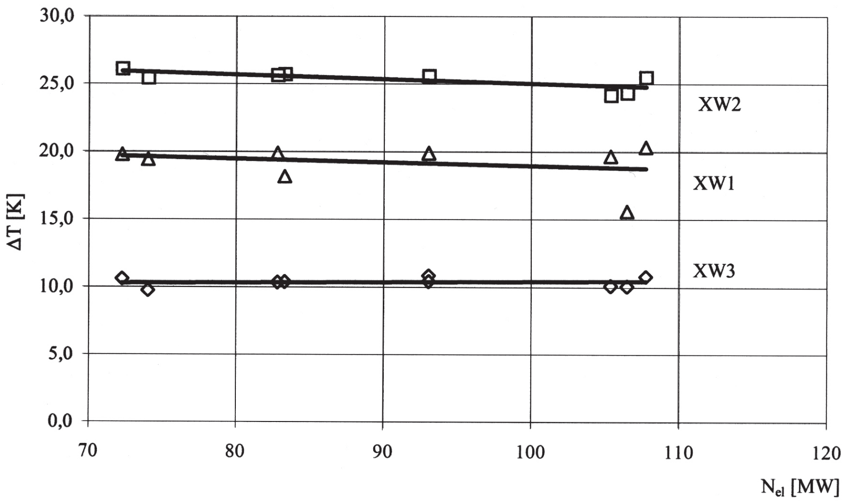

Fig. 15. Temperature difference ΔT between the media in heaters in the range of operating loads in the heating mode of operation

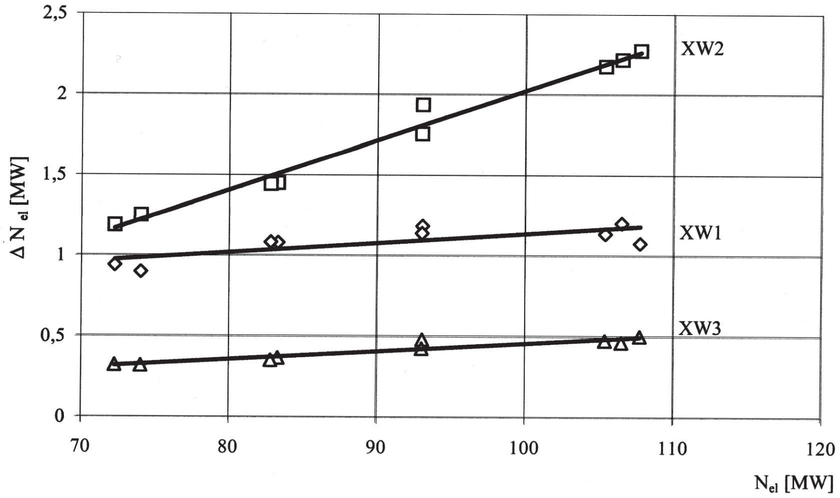

Fig. 16. Fluctuations of electric power ΔN_{el} for the heating mode of operation

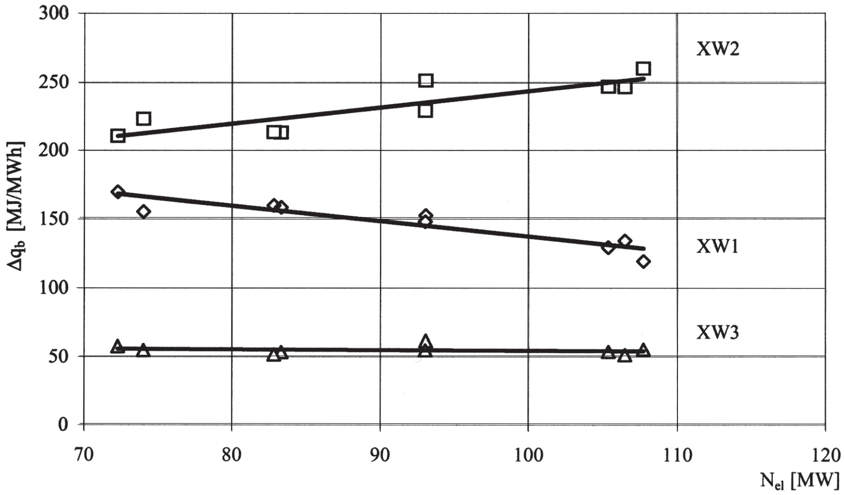

Fig. 17. Fluctuations of heat consumed in the block Δq_b for the heating mode of operation

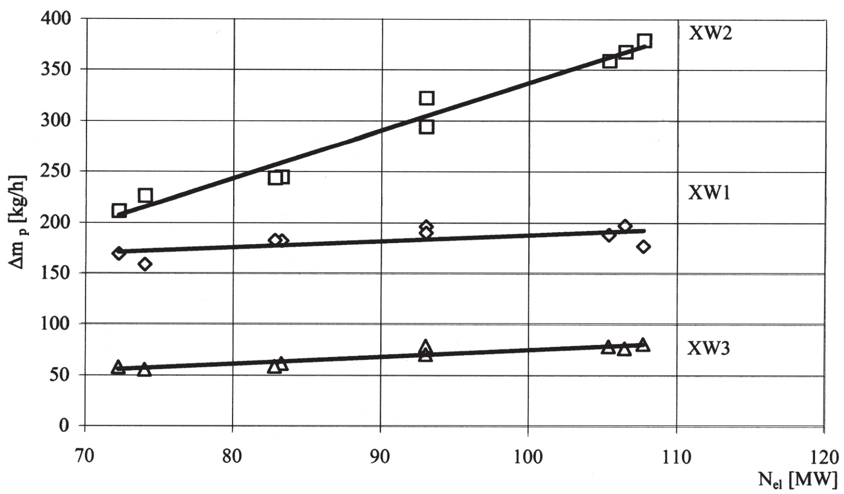

Fig. 18. Fluctuations of fuel consumption in the unit Δm_p for the heating mode of operation

For the economy load N_{el} = 106.48 MW its values in the heating mode of operation are:

- ΔT = 18.8 K (15.6 K) for heater XW1,
- ΔT = 24.3 K for heater XW2,
- ΔT = 10.0 K for heater XW3.

It is apparent that values of ΔT are established for each exchanger throughout the whole range of operating loads. Similar to the condensing mode of operation, the work load characteristics reveal that the proportion of losses in the exchanger XW2 proves to be the largest, next a smaller in XW1 and in XW3 – evident the smallest. Variation of power ΔN_{el}, of heat consumption by the unit Δq_b and associated changes in fuel consumption Δm_p are presented in the form of work load profiles, in a similar manner as in the condensing mode. Figure 16 shows profil of power fluctuations ΔN_{el} on the generator terminals in the function of work load.

Figure 17 shows profiles of fluctuations of heat consumption Δq_b by the unit due to thermodynamic loss, in the function of work load. The next characteristics is that of fuel consumption fluctuations Δm_p in particular heaters throughout the investigated range of operating loads (Fig. 18). The amounts of heat consumed by the power unit q_b in the whole range of operating loads are given in Figure 19. Similar to the condensing mode of operation case (see Fig. 10), the minimal value of q_b is achieved for the economy load in the heating mode of operation.

The amount of fuel used in the boiler operating in that mode and under the economy load N_{el} =106.48 MW is m_p = 62 956 kg/h. The sum total of fuel consumption fluctuations in the heating mode due to the loss amounts to $\sum\Delta m_p$ = 642 kg/h, which accounts for 1.03% of the total fuel consumption. Assuming the price of 1 ton of coal as fuel to be the same, we compute the proportion of costs due to increased fuel consumption caused by thermodynamic loss in the overall costs of electricity and heat generation in the unit. Annual costs caused by increased fuel consumption in individual exchangers in high-pressure regeneration systems: XW1, XW2, XW3 are graphed in Figure 20. Overall annual costs of due to increased fuel consumption associated with thermodynamic losses in the high-pressure regeneration system of the extraction condensing power unit in the heating mode of operation approach ΣK_R = 256 622 €.

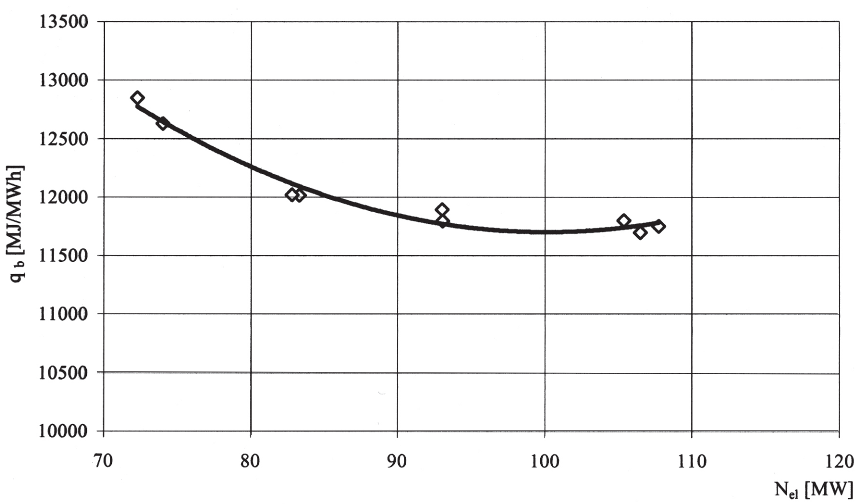

Fig. 19. Heat consumption in the unit q_b for the heating mode of operation

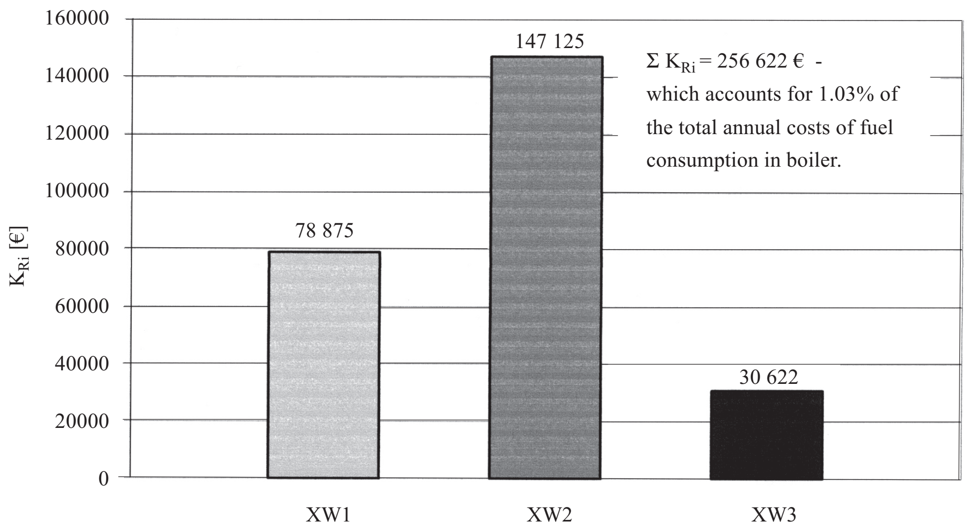

Fig. 20. Annual costs due to excessive fuel consumption K_{Ri} caused by thermodynamic losses in the high-pressure regeneration system for the economy load N_{el} =106.48 MW – heating mode of operation

5. CONCLUSIONS

The analysis of thermodynamic losses in the high-pressure regeneration system in the power unit no 2 allows for finding the individual exchangers' contributions to the loss balance in the investigated range of operating loads for the heating and condensing modes of operation. It appears that the highest losses occur in the heater XW2, which is attributable to the largest temperature difference between the superheated steam and the feed water to the boiler (high values of secondary superheated steam parameters). The characteristics reveal that the losses due to increased fuel consumption grow in proportion to the work load of the power unit. Measurements were taken in the high-pressure regeneration system of the extraction condensing type unit and the losses due to increased fuel consumption are determined for the economy load and in the two available modes of unit operation.

1) Condensing working mode:

Economy load of unit	N_{el} = 109.10 MW.
Fuel consumption in the unit	m_p = 59 179 kg/h.
Annual costs of fuel consumed by the unit	K_R = 23 671 000 €.
Sum total of increases of fuel consumption due to the loss in XW	$\sum\Delta m_p$ =452.4 kg/h.
Annual costs due to increased fuel consumption in XW	$\sum K_R$ = 180 962 €.
Fraction of annual costs due losses in fuel consumption	K_{Rp} = 0.77%.

2) Heating working mode:

Economy load of unit	N_{el} = 106.48 MW.
Fuel consumption in the unit	m_p = 61 956 kg/h.
Annual costs of fuel consumed by the unit	K_R = 24 782 000 €.
Sum total of increases of fuel consumption due to the loss in XW	$\sum\Delta m_p$ = 641.6 kg/h.
Annual costs due to increased fuel consumption in XW	$\sum K_R$ = 256 621 €.
Fraction of annual costs due losses in fuel consumption	K_{Rp} = 1.03%.

These thermodynamic losses in the regeneration systems, expressed in terms of excessive fuel consumption in equivalent costs of fuel in euro, are considerable. In order to limit the impacts of thermodynamic losses, actions must be taken to minimise those losses. Though thermodynamic losses in regeneration systems cannot be wholly eliminated, there are methods to reduce them. One has to bear in mind, however, that in order to minimise thermodynamic losses it is required that thermal power of media involved in regeneration processes be equal. In the case of high-pressure regeneration systems of the extraction condensing type unit no 2 in the combined heat and power plant EKC “Kraków S.A.” utmost care must be taken to precisely select the parameters of steam supplying the heaters. Parameters of superheated steam should be modified accordingly in a multi-section exchanger utilising the heat of superheated steam. Thus prepared steam ought to supply the exchangers XW. Potentials of modernisation of the existing high-pressure regeneration installation in the BC-90 unit with an eye to minimise thermodynamic losses will be explored in the next publications.

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