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THE INFLUENCE OF THE HEAT TRANSFER COEFFICIENT VARIATIONS IN THERMAL SYSTEM ELEMENTS ON POWER AND DISTRIBUTION OF EXERGETIC LOSSES IN THE PWR NUCLEAR POWER PLANT

The paper shows the results of a study on the influence of the changes of the heat transfer coefficient k on the exergetic losses in some selected equipment components of the thermal system and on the alternations of unit electric power. The changes of the k may be due to the fouling of the heat exchange surfaces or errors in the design. This research concerned with two feed-water heaters (low- and high-pressure) and the steam reheater situated behind the moisture separator. The research was conducted for the range of the ratio κ (of actual to the design value of k) from 0.5 to 1.5 of its value assumed in the design. The mathematical model considers off-design operating conditions in the whole thermal system, which result from the change of the coefficient k in the selected parts of the thermal system. The decomposition method and Seild's multilevel iterative process were used to solve the problem. The research proved that the capacity of the unit during operation may differ from the design value – 1000 MW – from ten to twenty MW due to alternations of the operation value of k from the design one.

NOMENCLATURE

k	– overall heat-transfer coefficient, kW/(m^2·K)
$n_q = P/Q_E$	– the ratio of the variation of the power plant capacity to the duty of the heat exchanger, kW/MW
P	– electric power, MW
q	– net plant heat rate, kJ/kW·h
Q_E	– heat exchanger duty, MW
$\delta \Pi_i = \Pi_{Ei} - \Pi_{Pi}$	– exergy losses in the i-th part or in the set of parts, MJ
Δ	– the change of the parameter
$\kappa = k/k_0$	– ratio of actual to the design value of overall heat-transfer coefficient
Π_{Ei}, Π_{Pi}	– exergy losses in the i-th equipment component for the operation (E) and design (P) value of the coefficient k

INTRODUCTION

The efficiency of the condensing power station, inter alias, depends on the conditions of heat transfer in surface heat exchangers. The exchangers play a significant role being involved in the thermodynamic processes composing the steam cycle. The overall heat transfer coefficient k reflects the conditions mentioned above.

Actual values of the overall heat transfer coefficient k in feedwater heaters and in other heat exchangers of the plant often differ during the operation from the design values. These differences may be due to the fouling on the heat exchange surfaces or to the errors in calculation of the surface and heat transfer coefficients. When the value of the coefficient k decreases, then the terminal temperature difference increases. The exergetic losses due to irreversibility of the heat transfer processes also increase. The power and efficiency of the unit decreases as well.

1. ASSUMPTIONS

The analysis was conducted for a condensing power plant unit, of 1000 MW electric power, with the PWR reactor. The turbine consists of the high-pressure part (THP), middle-pressure part (TMP) and three identical low-pressure parts (TLP). The two-stage moisture separators are mounted in the turbine ducts THP-TMP and TMP-TLP. Moreover in the TMP-TLP turbine duct the steam is superheated in the reheater (ESR) fed by the heating steam from the steam extraction of the THP turbine. In the regeneration system there are four low--pressure feed-water heaters (ELP), deareator and the high-pressure feedwater heater (EHP). The pump is fed by the steam taken behind the reheater.

The flow sheet of the nuclear power plant is shown in Fig.1. The main design thermodynamic parameters (pressure and temperature) of the steam cycle are marked on the sheet. According to the design assumptions, the pressure of the steam feeding the ELP-2 heater equals 0.113 MPa and the condensate is heated in it from 74.8 to 100.2°C. In the feedwater heater EHP the pressure of the heating steam equals 2.63 MPa and the water is heated from 190.2 to 220.2°C. In the reheater ESR the pressure of the heating steam equals 3.4 MPa and the pressure and temperature of the preheated steam at the outlet equal 0.77 MPa and 216.2°C, respectively. The terminal temperature differences in the following exchangers: ELP-2, EHP and ESR equal 2.9, 6.5, 25°C and nominal value of the coefficient k equals 3.4, 4.6, 0.60 kW/m$^2\cdot$K, respectively. In Fig.1 the heat exchangers for which the study of the influence of the changes of the coefficient k on the power and exergetic losses was carried out are marked with a bold line.

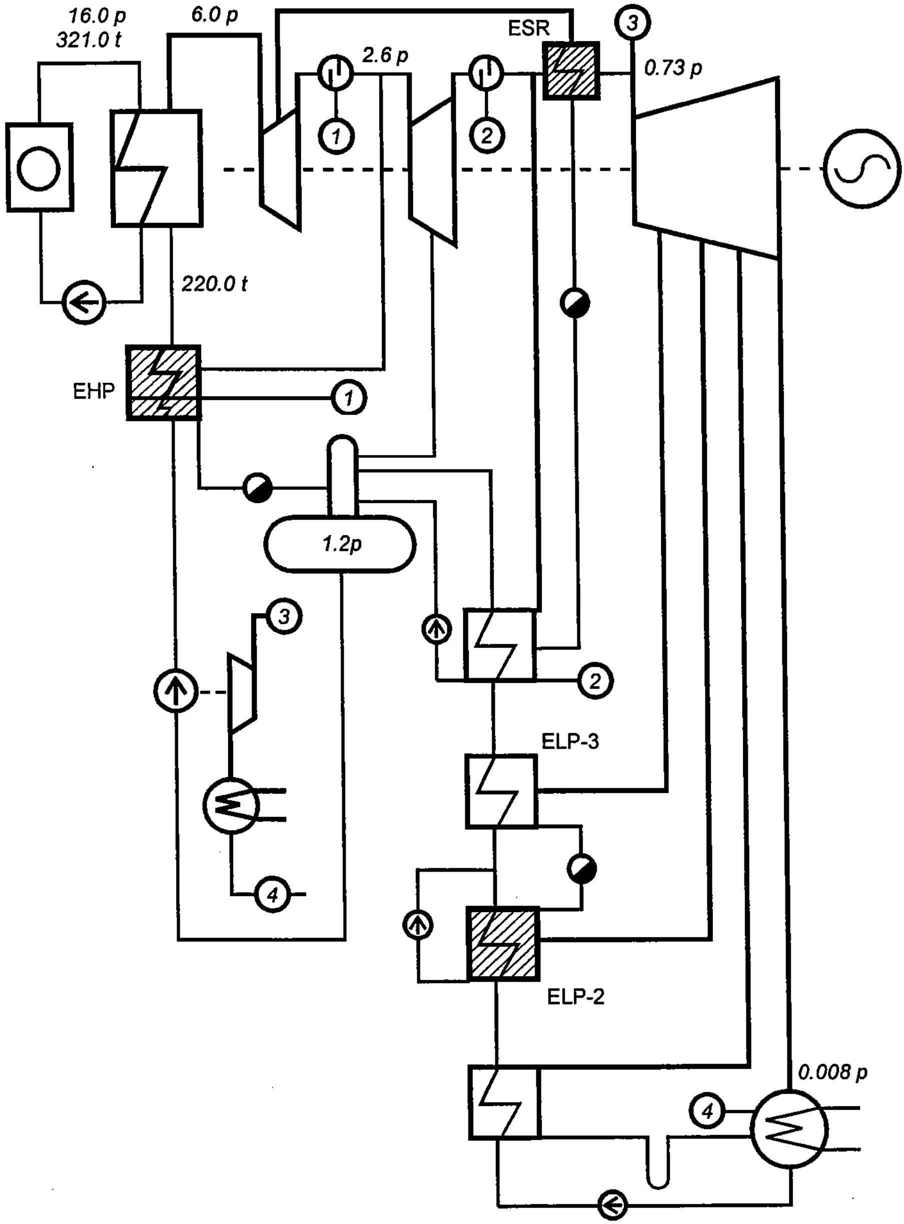

Fig. 1. Flow sheet of the nuclear power plant: (p – pressure [MPa], t – temperature [°C])

2. MATHEMATICAL MODEL AND NUMERICAL METHOD OF CALCULATIONS

The model allows to carry out the studies on the influence of the coefficient k on the change of electric power of the power plant unit and on the change of exergetic losses in the particular parts of the unit. The losses are calculated not only for the heat exchangers in which the change of the conditions of heat transfer occurs but also in all other elements of the heat flow diagram of the power plant.

The model consists of the following segments:

MBE – a set of mass and energy balance equations. This segment enables the solution of the so-called balance problem, that is, for input thermodynamic parameters it allows the evaluation of mass and energy flows. The segment consists of the equations of the mass and energy balance mainly, most of which are linear.

MPT – a set of thermodynamic parameters equations. This segment allows the evaluation of the thermodynamic parameters for the given mass flowrates. This segment also includes equations describing heat transfer, pressure loss and changes of the parameters in the turbine. The segment consists of the equations most of which are nonlinear. The heat transfer in the feedwater heaters was described by the formulas given in [5].

MPP – a set of power plant thermal performance. This segment allows the evaluation of the exergetic losses, the net power plant heat rate, energy consumption necessary for the unit efficiency and self-needs. The values obtained in the MBE and MPT segments are used to evaluate the coefficients mentioned above.

The problem was solved by means of a general method of defining the state of the thermal system at off-design operating conditions that was published in [4]. This method is similar to the one proposed in [3]. A simplified scheme of this method, which has been used in this paper, is shown in Fig. 2. Having stated the assumptions concerning the operating conditions of the power plant unit and starting approximation of the solution (A), the following operations are made in the j-th step of the iteration process.

1. The evaluation of mass and energy flows M^j based on the MBE model.
2. The evaluation of the thermodynamic parameters PT^j based on the MPT model and on the M^j.

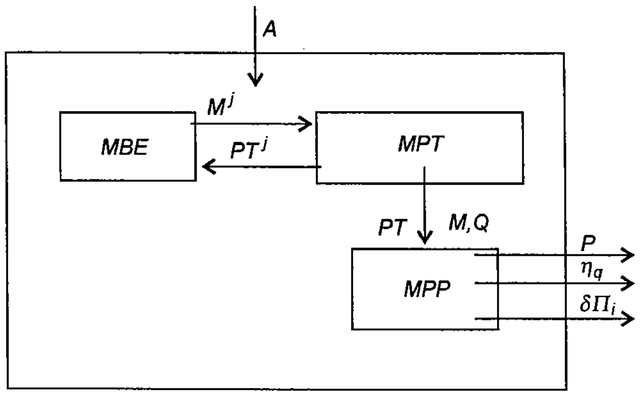

Fig. 2. The scheme of solution method: A – assumptions, PT – thermodynamic parameters of the power plant, P – electric power, η_q – the change of the electric power of the unit related to the thermal power of a heat exchanger, $\delta\Pi_i$ – exergy losses in the i-th part or in the set of parts

Then the operation is repeated as in points 1st and 2nd till the conditions of the iteration process are satisfied. Then the balance problem is solved again. The evaluation of the quantities defined in the MPP model is in the last part of the calculation.

3. RESULTS

The dependence of the variation of the electric power of the power station unit P and of the net plant heat rate q on the relative change of the overall heat transfer coefficient κ (that is the ratio of the real operation to the design value of overall heat transfer coefficient k) is shown in Fig. 3.

The results concern the low-pressure ELP-2 and high-pressure EHP feed--water heaters and steam reheater ESR. The decrease of the coefficient k in the reheater results in the highest loss of power, whereas the decrease of the coefficient k in the ELP-2 exchanger results in the lowest loss of power. For κ varying from 1.5 to 0.5 the decrease of power equals 2.3 MW, 3.8 MW and 6.8 MW in the case of the change of the operating conditions in the ENP-2, EHP feedwater heaters, and in the ESR steam reheater, respectively. The changes of the capacity of the power plant unit depend not only on the change of the coefficient k but also on the duty of the heat exchangers. The results, which are shown in Fig. 3., consider the influence of both variables mentioned above.

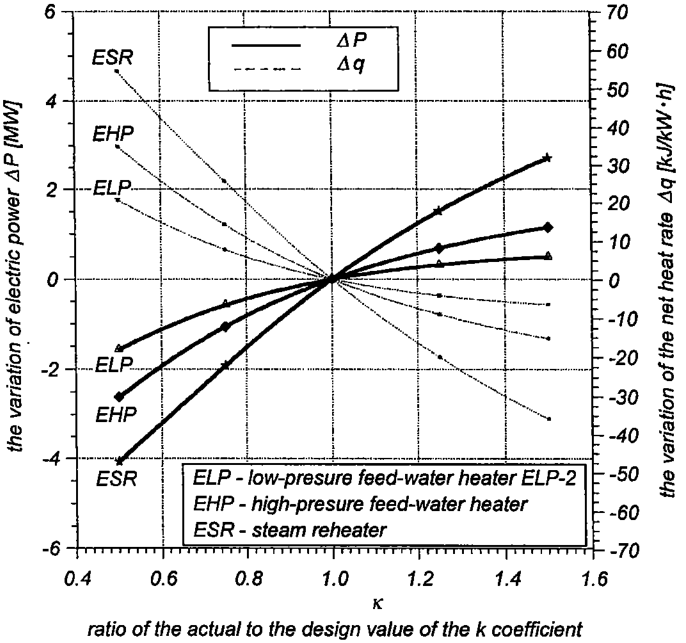

Fig. 3. Capacity of the power plant unit P and net heat rate q versus overall heat transfer coefficient $\kappa = k/k_0$

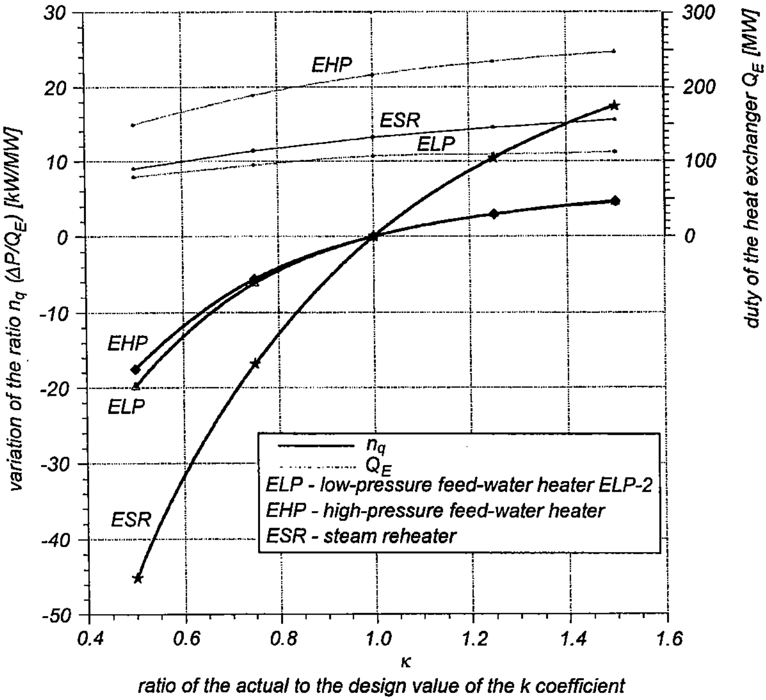

Fig. 4. Ratio n_q (the change of electric power ΔP related to the heat exchanger duty) and the heat exchanger duty Q_E versus the overall heat transfer coefficient $\kappa = k/k_0$

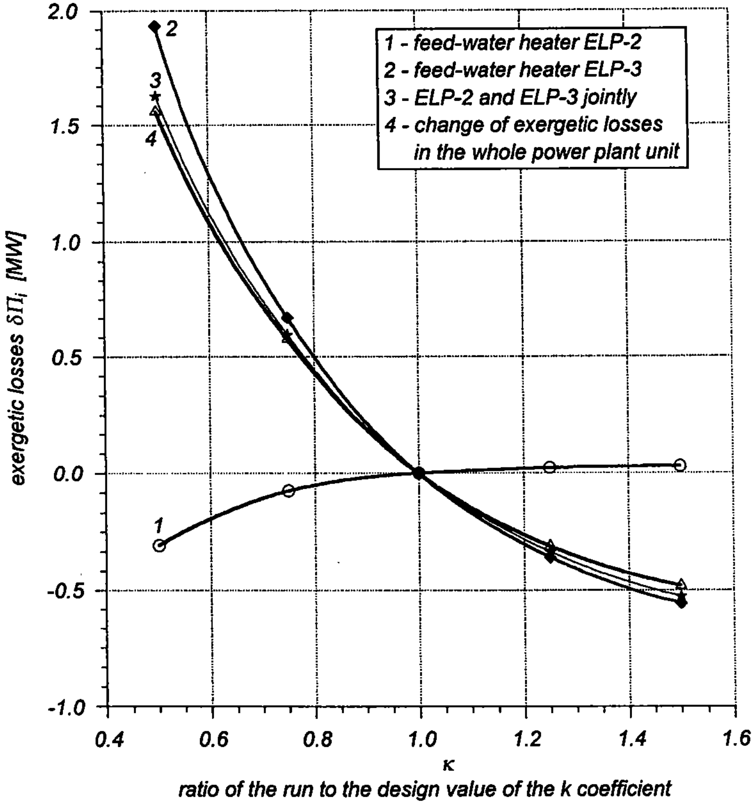

Fig. 5. The dependence of the power plant exergetic losses variation and of the losses in the selected power plant equipment components $\delta \Pi_i$ on the ELP-2 overall heat transfer coefficient $\kappa = k/k_0$

The relative change of the unit power related to the duty of the heat exchangers is shown in Fig. 4.

Maximum change of the relative decrement n_q for the ELP-2 feed-water heater, equals 24 kW/MW, for EHP and for ESR it equals 22 kW/MW and 62 kW/MW, respectively. The same (as above) change of the k coefficient results in the higher relative power decrement in the ELP-2 feed-water heater than in the EHP one due to the lower level of temperatures in the ELP-2 heat exchanger than in the EHP high-pressure exchanger. In Fig. 4 the dotted lines present the dependence of the duty (thermal power) of the ELP-2, EHP and ESR heat exchangers on the changes of the ratio κ.

The overall change of exergetic losses and the change of losses in the selected parts of the power plant thermal system resulting from the change of the coefficient k in the ELP-2 feed-water heater are shown in Fig. 5. The total changes of exergetic losses in the unit are close to the global change in the ELP-2 exchanger and in the next ELP-3 feed-water heater. In the remaining parts of the thermal system the changes are much lower, that is approximately about ten times lower.

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WPŁYW ZMIAN WSPÓŁCZYNNIKA PRZENIKANIA CIEPŁA W ELEMENTACH UKŁADU CIEPLNEGO NA MOC I ROZKŁAD STRAT EGZERGETYCZNYCH W JĄDROWYM BLOKU ENERGETYCZNYM Z REAKTOREM TYPU PWR

Streszczenie

W pracy zostały przedstawione wyniki wpływu zmian współczynnika przenikania ciepła w wymiennikach powierzchniowych (k) na straty egzergetyczne w wybranych elementach układu cieplnego i zmiany mocy elektrycznej bloku energetycznego. Zmiany k mogą być spowodowane zanieczyszczeniami powierzchni wymiany ciepła lub błędami w opisie wymiany ciepła przy projektowaniu. Badania zostały przeprowadzone w zakresie względnych zmian współczynnika przenikania od 0,5 do 1,5 jego wartości przyjętej przy projektowaniu i dotyczą dwóch wymienników regeneracyjnych (nisko- i wysokoprężnego) oraz przegrzewacza pary za separatorem wilgoci.

Opracowany model matematyczny uwzględnia zmienne warunki pracy układu cieplnego, wynikające ze zmiany współczynnika k. Do numerycznego rozwiązania zadania wykorzystana została metoda dekompozycji oraz wielopoziomowy proces iteracyjny Seidla.

Badania wykazały, że moc projektowanego bloku – 1000 MW, z powodu odbiegających podczas eksploatacji wartości *k* (w stosunku do przyjętych przy projektowaniu), może ulec zmianie od kilku do kilkunastu MW (do 2%).

ВЛИЯНИЕ ИЗМЕНЕНИЙ КОЭФФИЦИЕНТА ТЕПЛОПЕРЕДАЧИ В ЭЛЕМЕНТАХ ТЕПЛОВЫХ СХЕМ НА МОЩНОСТЬ И РАСПРЕДЕЛЕНИЕ ЭГЗЕРГЕТИЧЕСКИХ ПОТЕРЬ В ЯДЕРНОМ ЭНЕРГЕТИЧЕСКОМ БЛОКЕ С РЕАКТОРОМ ТИПА ВВЭР

Краткое содержание

В работе представлены результаты исследований влияния изменений коэффициента теплопередачи в поверхностных теплообменниках (*k*) на эгзергетические потери в избранных элементах тепловой схемы и изменения электрической мощности энергетического блока. Изменения *k* могут быть вызваны загрязнениями поверхности теплообмена или ошибками в описании процесса теплообмена при проектировании. Исследования были проведены в пределах относительных изменений коэффициента теплопередачи от 0,5 до 1,5 его значения принятого при проектировании и касаются двух регенеративных обменников (низкого и высокого давления) и перегревателя пары за сепаратором влаги.

Выработанная математическая модель учитывает переменные режимы работы тепловой схемы, возникающие при изменении коэффициента *k*. К числовому решению задания применен метод декомпозиции, а также многоступенчатый итерационный процесс Зайдля.

Исследования показали, что мощность проектируемого блока – 1000 МВт, из-за отклоняющихся во время эксплуатации значений *k* (в отношении *k* принятым при проектировании) может изменяться до 2%.