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Influence of Regenerative Feed Water Heaters on the Operational Costs of Steam Power Plants and HP Plants

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Abstract

The influence of particular regenerative feed-water heaters on the operational costs of a steam power plant and HP plant has been determined by means of the incremental energy efficiency expressing the ratio of the increase of electricity production to the increase of the consumption of chemical energy of fuel, assuming a constant flow rate of steam at the outlet of the turbine (power plant) or a given production rate of useful heat (HP plant). Exemplary calculations are included.

Keywords: Feed water heaters, operational cost

1. Introduction

Regenerative preheating of feed water in steam power plants and HP plants by means of the steam taken between the stages of the turbine is a special case of the cogeneration of heat and mechanical work, because the heat is delivered by a steam flux, which has previously performed some amount of work (Drbal et al., 1995). The delivered heat remains, however, inside the system. The attained positive effects may be evaluated by means of the investigation of the influence of heat regeneration on the production of electricity and consumption of fuel. The influence of particular bleeds may be separately determined by means of an incremental efficiency expressing the ratio of the increase of the useful effect to the consumption increase of the chemical energy of fuel, assuming a constant value of some parameter P characterising the process (Szargut, 1999). It is convenient to analyse in the considered case the incremental efficiency of the electricity production:

$$\eta_\Delta = \left(\frac{\Delta E_{el}}{\Delta E_{ch}}\right)_{P=const} \tag{1}$$

The effect of the analysis depends on the selection of the constant parameter P. In (Szargut, 2004) it has been assumed a constant flux of fresh steam. Such an assumption is not convenient when analysing the HP plant, because in that case the heat demand is given. Therefore, in the case of the HP plants, it has been assumed that the parameter P expresses the given heat demand. Similarly, in the case of power plants, a constant value of the steam flux flowing out from the turbine to the condenser has been assumed. The cited assumptions lead to a surprisingly simple solution.

Different assumptions of the parameter P lead to different results in the analysis of operational costs. However, it should be stressed that this analysis represents only the first step in the economic analysis of the considered technology. In the second step the analysis of the influence of regenerative heating of feed water on the investment expenditures would be necessary. The components of the second step would also depend on the selection of the parameter P. The sum of both mentioned effects should not depend on the selection of that parameter. However, the analysis of the influence of the considered technology on the investment costs of a power or HP plant would be very difficult, if altogether possible. The analysis of the operational costs gives some preliminary information about the economic effects of the regenerative heating of water. The mentioned causes indicate that the accepted assumptions should ensure a possibly simple form of the solution.

2. Incremental Efficiency in a Condensation Power Plant

The assumption of a constant steam flux flowing to the condenser results in the following additional production of electricity after switching on an ith bleed:

$$\Delta \dot{E}_{el\,i} = \eta_{me} \Delta \dot{G}_i \left(i_1 + i_2 + i_3 - i_{ui} \right) \qquad (2)$$

where η_{me} is the electro-mechanical efficiency of the turboset, $\Delta \dot{G}_i$ the steam flux taken from the ith bleed, i_1, i_2, i_3 are the specific enthalpies of the fresh steam and steam before and after the secondary superheater, and i_{ui} is the specific enthalpy of steam in the ith bleed.

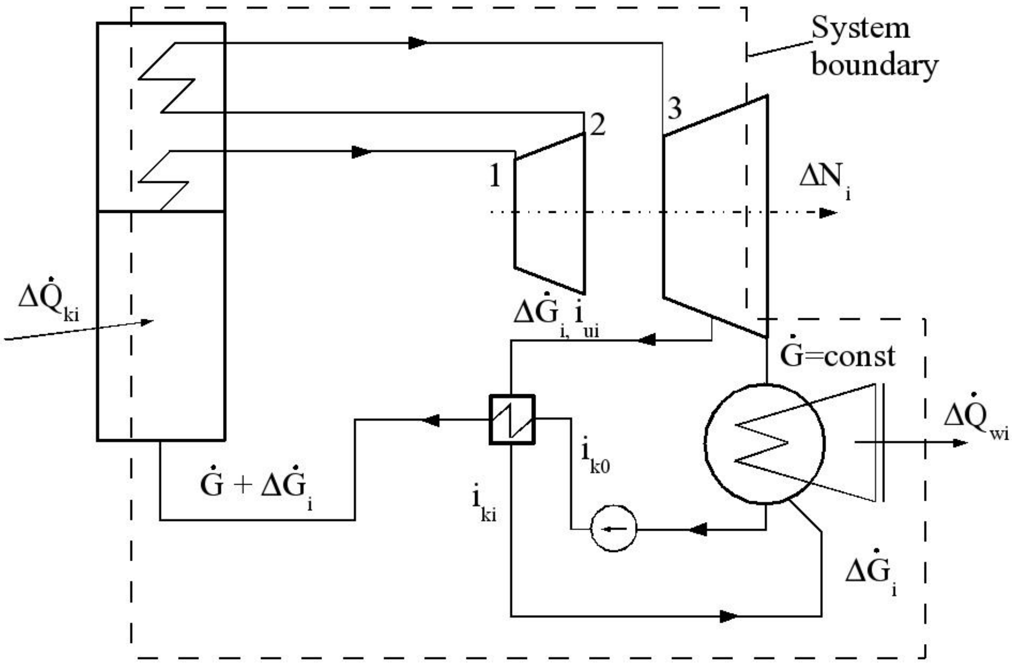

Figure1. Scheme of steam power plant.

The heat demand inside the boiler increases after switching on the regenerative bleed. That increase equals the increase of the internal power of the turbine if the condensate of the bleed steam does not flow to the main condenser. That conclusion results from the energy balance of a system whose boundary runs along the external surfaces of the heated elements of the boiler and encloses the internal part of the turbine (except the places of mechanical friction), the main condenser and the regenerative heaters. When the condensate of some bleed steam flows to the main condenser, the heat rejected in the main condenser increases and the same increase of heat demand appears in the boiler (*Figure 1*). The increase of the demand for chemical energy in the boiler caused by switching on the regenerative bleed may be expressed in this case as follows:

$$\Delta \dot{E}_{ch\,i} = \frac{1}{\eta_{Ek}} \Delta \dot{G}_i \begin{pmatrix} i_1 - i_2 + i_3 - \\ i_{ui} + i_{ki} - i_{ko} \end{pmatrix} \qquad (3)$$

where η_{Ek} is the energy efficiency of the boiler and i_{ki}, i_{ko} are the specific enthalpy of the condensate of the bleed steam flowing from the ith heater to the main condenser and of the main condensate flowing out from the condenser.

When the bleed steam is extracted before the secondary superheater, or that superheater does not appear in the considered plant, it should be inserted in equations (2) and (3) $i_2 = i_3$. The following formula expressing the incremental energy efficiency of the additional production of electricity after switching on an ith regenerative bleed results from equations (2) and (3):

$$\eta_{\Delta i} = \frac{\eta_{Ek} \eta_{me}}{1 + \dfrac{i_{ki} - i_{ko}}{i_1 - i_2 + i_3 - i_{ui}}} \qquad (4)$$

The numerator of equation (4) should be taken into account only if the condensate of the bleed steam does not flow to the main condenser.

3. Economy of the Operational Costs

The yearly economy of the operational costs due to the regenerative preheating of feed water comprises the income ΔK_{el} from the sale of additional amount of electricity and the expenditure ΔK_F for the additional consumption of fuel:

$$\Phi = \Delta K_{el} - \Delta K_F \qquad (5)$$

Assuming a constant load of the power plant, the following formula for the yearly income from the additional sale of electricity due to the operation of ith heater may be applied:

$$\Delta K_{el\,i} = \tau_n k_{el} \Delta \dot{E}_{el\,i} \qquad (6)$$

where τ_n is the annual utilisation time of the considered load and k_{el} the specific sale price of the electricity.

The yearly increase of the expenditure for fuel may be calculated by means of the incremental energy efficiency:

$$\Delta K_{Fi} = \frac{k_F}{k_{el}} \frac{\Delta K_{el\,i}}{\eta_{\Delta i}} \tag{7}$$

where k_F is the specific cost of the chemical energy of fuel.

4. Example 1

TABLE I contains the exemplary measurement results of a condensation power plant with a nominal power of 360 MW (Rusinowski et al., 2000). The following data have been used in exemplary calculations: energy efficiency of the boiler η_{Ek} = 0.935, electromechanical efficiency of the turboset η_{me} = 0.97, specific enthalpy of the fresh steam i_1 = 3389 kJ/kg, of the steam before the reheater i_2 = 3017 kJ/kg, after the reheater i_3 = 3544 kJ/kg, specific enthalpy of the condensate flowing out from the first (with the lowest pressure) water heater i_{k1} = 273.2 kJ/kg, enthalpy of the main condensate flowing out from the condenser i_{ko} = 146.3 kJ/kg.

The considered plant has three water heaters in the low-pressure part, one between the low pressure and middle pressure part, a degasifier operating simultaneously as a mixing heater, one heater in the middle-pressure part, one between the middle-pressure and the high-pressure part and one in the high-pressure part. The bleed steam condensate from the first heater flows to the main condenser, from heater 3 to heater 2, and from that heater to the main condensate pipeline by means of an auxiliary pump. The bleed steam condensate from the heater 4 is delivered by means of another pump to the main condensate pipeline. The condensate of the bleed steam from the heaters 6 and 7 flows to the degasifier. The bleed 7 is located before the reheater. Only in that case it should be inserted in equation (2), (3), (4): $i_2 = i_3$.

In TABLE II the values of the yearly economy of the operational cost are cited, separately for particular heaters. The sale price of electricity k_{el} = 30 zl/GJ and the purchase price of the chemical energy of coal k_F = 7 zl/GJ has been assumed (1 zl= 0.25 US$). The yearly utilisation time of the nominal power is τ_n = 7200 h/year.

5. Effects Attained in a HP Plant

When analysing the HP plant, the condensation stream and the back-pressure stream should be considered separately. The condensation stream should be treated similarly as in the condensation power plant. When considering the back pressure stream, a given demand for useful heat should be assumed. Therefore, the switching on of the regenerative bleed causes only an increase in the internal power of the turbine and the same increase in the heat delivered to the working fluid in the boiler. The incremental energy efficiency of the production of electricity again equals the product of the energy efficiency of the boiler and the electro-mechanical efficiency of the turboset. When, however, the condensate of the bleed steam flows to the heat exchanger heating the network water, the flow rate in the final part of the turbine changes, and the electricity production in that part becomes smaller. A comparison of two energy balances of the boiler (before and after switching the regenerative heater, *Figure 2*) results in the following formula expressing the increase of the heat demand in the boiler:

$$\Delta\dot{Q}_k = \left(\dot{G}'_g + \Delta\dot{G}\right)\left(i_1 - i_6\right) - \dot{G}_g\left(i_1 - i_3\right) \tag{8}$$

From the condition of a constant heat production it results:

$$\dot{G}_g\left(i_2 - i_3\right) = \dot{G}'_g\left(i_2 - i_3\right) + \Delta\dot{G}\left(i_5 - i_3\right) \tag{9}$$

The energy balance of the regenerative heater has a form:

$$\left(\dot{G}'_g + \Delta\dot{G}\right)\left(i_6 - i_3\right) = \Delta\dot{G}\left(i_4 - i_5\right) \tag{10}$$

Equations (9) and (10) enable us to eliminate the quantities $\dot{G}_g$ and $\dot{G}'_g$ from equation (8) after what it result

$$\Delta\dot{Q}_k = \Delta\dot{G}\left(\frac{i_2 - i_5}{i_2 - i_3}\left(i_1 - i_3\right) - \left(i_4 - i_5\right)\right) \tag{11}$$

The final result expresses the additional production of electricity:

$$\Delta\dot{E}_{el} = \eta_{me}\Delta\dot{Q}_k \tag{12}$$

6. Example 2

According to the measurements and calculation results cited in Rusinowski et al. (2000), it has been assumed i_1 = 3594.3 i_2 = 2690.4 i_3 = 364.2 i_4 = 2867.6 i_5 = 528.9 kJ/kg, $\Delta\dot{G}$ = 16 t/h. From equation (11) it results $\Delta\dot{Q}_k$ = 2.943 MW and $\Delta\dot{E}_{el}$ = 2.857 MW. The values of the economic indices have been assumed according to the section Example 1. The yearly operation time with the assumed load τ_n = 2000 h/year (mean value of some interval of the duration curve of load). From equations (5) and (7) ΔK_{el} = 0.617 mln zl/year, ΔK_F = 0.159 mln zl/year. The yearly economy of the operational costs ΔK_{op} = 0.458 mln zl/year. There appears an essential difference between the methods of solution of the problem in the case of a condensation power plant and a steam HP plant. The condensation power plant can operate at a stabilized load and then the calculation is not difficult. In a HP plant the load depends on the demand for useful heat. Therefore, not only does the flow rate of the outlet steam change, but also the flow rate of the bleed steam extracted to feed the peak water heater.

The changes of the flow rate of steam cause a change of the pressure distribution in the steam bleeds. The regenerative bleeds are not regulated, and therefore, the flow rate of the regenerative steam is determined by the conditions of heat transfer in the regenerative heaters, mainly by the steam temperature (depending on pressure). The calculation method of the changes of pressure in the turbine bleeds has been presented in (Szargut,1999). It requires an elaboration of a mathematical model, taking into account the duration curve of heat demand.

TABLE I. PARAMETERS OF THE BLADE STREAMS AND INCREMENTIAL ENERGY EFFICIENCY OF THE ADDITIONAL PRODUCTION OF THE ELECTRICITY IN THE STEAM POWER PLANT.

Heater number	1	2	3	4	5	6	7
Pressure in the bleed, MPa	0.030	0.089	0.242	0.438	0.88	1.85	3.92
Stream of the bleed steam, t/h	44.0	26.1	64.5	20.9	32.6	44.0	97.9
Specific enthalpy of steam, kJ/kg	2532.5	2690.4	2867.6	2991.4	3142.4	3332.3	3033.1
Incremential energy efficiency of the additional production of electricity	0.833	0.907	0.907	0.907	0.907	0.907	0.907

TABLE II. DECREASE OF THE OPERATIONAL COSTS OF THE TURBOSET DUE TO THE REGENERATIVE PREHEATING OF THE FEED WATER.

Heater number	1	2	3	4	5	6	7
Additional production of electricity, PJ/year	403.2	231.6	492.5	135.0	176.1	179.4	243.3
Additional consumption of chemical energy, PJ/year	484.0	255.3	543.0	148.8	194.2	197.8	268.2
Additional income from the electricity sale, mln zl/year	12.096	6.948	14.776	3.727	5.284	5.381	7.298
Additional cost of fuel, mln zl/year	3.388	1.787	3.801	1.042	1.359	1.385	1.877
Economy of operational costs, mln zl/year	8.708	5.161	10.975	2.685	3.925	3.996	5.421

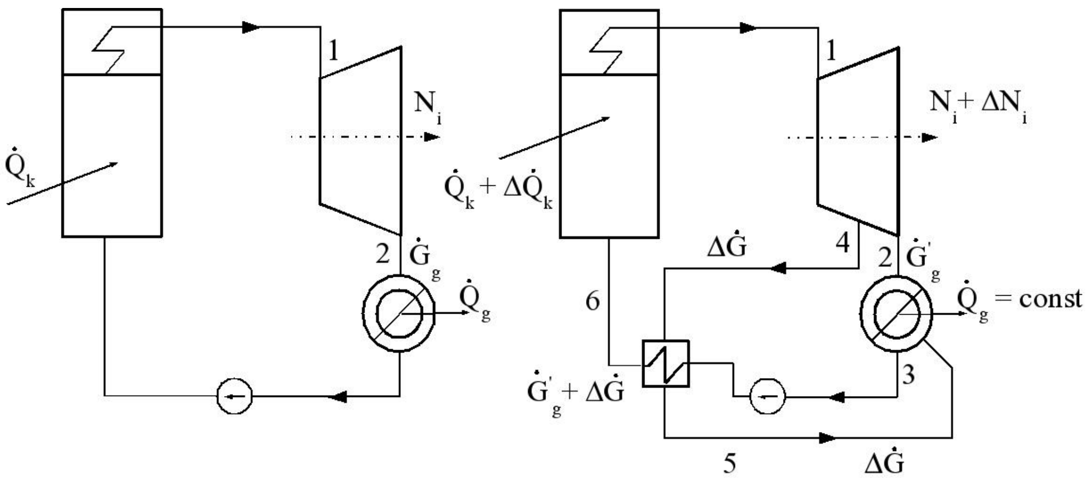

Figure 2. Schemes of a steam HP plant.

7. Conclusions

The influence of the regenerative feed water heaters on the operational costs of a steam power plant or an HP plant can be determined by means of the incremental energy efficiency, without analysing the efficiency of the total system. The presented method proves a very high energy efficiency of the regenerative preheating of the feed water. The effects are proportional to the amount of additionally produced electricity. It can be increased by reducing the irreversibility of the feed water heaters (increasing their amount and heat transfer area).

The presented method can be applied in condensation steam power plants and also steam HP plants. In the second case, the use of the duration curve of heat demand is necessary, along with its partition into time intervals and analysing the changes of pressure of the bleed steam due to the change of heat demand.

The analysis of the influence of feed water heaters on investment expenditures of the plant, would be more difficult. When analysing the power plant the accepted assumption of the parameter P permits acceptance of a constant investment cost of the condenser and water cooling system. The increase of the steam boiler capacity and the change of its operating conditions should be taken into account. The introduction of every regenerative feedwater heater requires an increase of the combustion air heater by means of gaseous combustion products, which increases the combustion temperature and the intensity of NOx formation. Hence, the means for the reduction of this formation should be enhanced. The height of the turbine blades in the turbine stages preceding the considered water heater should be taken into account. This effect improves the internal efficiency of the turbine, because the relative interstage gap losses become smaller. Additionally the investment costs of the water heaters and steam pipelines should be considered.

Nomenclature

E	amount of energy, kJ
G	amount of the working fluid, kg
i	specific enthalpy, kJ/kg
K	cost of energy, zl
k	specific cost of energy, zl/kg
Q	amount of heat, kJ
Δ	increase
$\Delta\dot{G}$	flow rate of bleed steam efficiency
η	efficiency
η_Δ	incremental energy efficiency
τ_n	yearly utilization of the nominal power

Subscripts

ch	chemical
E	related to energy
el	related to electricity
F	fuel
i	order number of the bleed
k	related to boiler or condensate
me	electro-mechanical
u	related to bleed steam
O	main condensate flow

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