TECHNICAL OPTIMIZATION OF THE REGENERATIVE PREHEAT LINE TEMPERATURE GROWTH'S REPARTITION, FOR REHEAT STEAM CYCLES

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This paper refers to high power steam units with elevated main steam parameters, steam reheat and advanced feed water preheat. For non-reheat steam cycles, an analytical demonstration, shows that maximal steam cycles thermal efficiencies are obtained for equals temperature's growths in feed water preheat stages. In reheat steam cycles, without extractions during the steam's expansion in turbine's High Pressure Cylinder, some papers recommend, in order to reduce the electricity price, a bigger temperature increase at the final preheat stage, supplied with steam from extraction amount of reheat. The paper pursue simultaneous technical optimizations, with economical consideration, of steam reheat pressure and feed water preheat temperature, with an optimal distribution of temperature's growth between the water preheat stages.

Because of the thermal scheme complexity, the great number of variables and transcendent equation involved, the study was elaborated through numerical simulation. We used validated methodologies, functions, and procedures, most of them conceived and in our chair. Simulation is performed only for stationary design load. Numerical examples that will be presented refer to usual data sets for high power steam cycles. The results demonstrate that it is impossible to maximize in the same time the thermal efficiency and the investment. An analysis taking into consideration three main criteria put into evidence that: ***a)*** *the optimal steam reheat pressure is about 24 % from the main steam pressure and* ***b)*** *optimal temperature growth for the final preheat stage is 1.4÷1.5 bigger then the temperature growth at the feed water preheat stages supplied with steam from extractions after reheat. Conclusions could be applied for new units design and existing units retrofit.*

Key words: Rankine Cycle, Steam Reheat, Feed Water Preheat, Optimization, and Computation.

1. Background. Presentation of thermal schemes.

The first class of methods for condensing steam cycle's performance increase is based on growing extreme cycle parameter difference (maximal / minimal). Rising the difference between the "external" parameters, imposed by

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thermal sources, assume: **A)** on hot source, increasing the average upper temperature (T_{ms}), by raising the main steam parameters (p_0 / t_0) and reheat temperature (t_{reh}), respectively **B)** on could source, decreasing the average inferior temperature (T_{mi}), through condensing temperature and pressure diminishing.

The second class depends on the "internal" parameters and is realized without changing the external ones – through "carnotization methods[4]" refers to:

- the structure/ complexity of scheme: number of reheats, number and type of preheat stages, the position of steam extraction relative to reheat(s), etc.;
- the way to correlate efficiency increasing methods: reheat pressure(s) as percentage(s) of main steam pressure, feed water temperature, preheat repartition by stages, etc.

In practice, the steam cycles improving methods are simultaneous and correlated applied. This paper refers to high power classical condensing steam cycles, with a single reheat, and having no extraction during the expansion in the high pressure cylinder. The number of preheat stages is z_{st} = 7 or 8. On analyzed scheme's notation (see figure 1 and 2) the first digit represent the total number of preheaters and the second digit, the number of surface Low Pressure Preheaters (LPP). The minimum number of High Pressure Preheaters (HPP) is two[5].

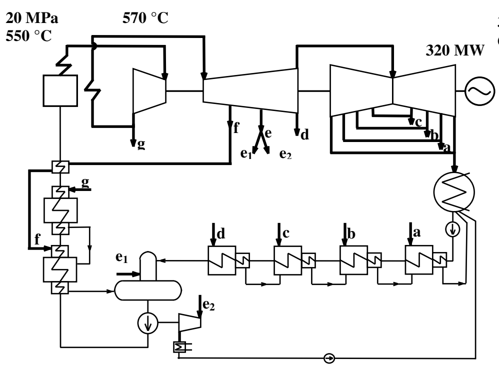

Fig. 1. The **„7_4"** design scheme.

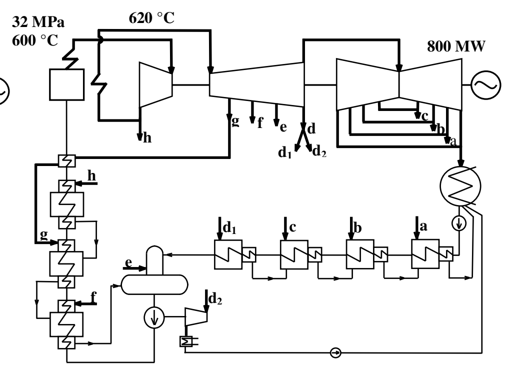

Fig. 2. The **„8_4"** design scheme.

The assumptions for thermal scheme generating are the following:

✶ Conform to [1], preheat stages supplied with steam behind the reheat, will have equal temperature growths.

✶ The penultimate preheat stage (in the order of feed water flow), supplied with steam from the first extraction after the reheat, will have a separate feat transfer surface mounted after the last preheat stage [2].

✶ The Deaerator will have sliding pressure.

✶ The main feed water pumps will be drive by condensing steam turbines.

✶ The number of surface low pressure stages will be greater than, or at least

[4] Methods witch improve the cycle by approaching his form to Carnot cycle one.

[5] The deaerator must not be feed with steam from the first extraction behind the reheat.

equal to, the number of surface high pressure preheaters.

The total number of preheat stages, the main steam parameters, and the units size will be correlated as following: for the scheme **„7_4"** will be consider $p_0 \in [20 \div 25]$ MPa, $t_0/t_{reh} \in [550 \div 580]$ °C, and $P_{bg} \in [320 \div 500]$ MW, while for **„8_4"** $p_0 \in [25 \div 32]$ MPa, $t_0/t_{reh} \in [580 \div 620]$ °C, and $P_{bg} \in [500 \div 800]$ MW.

2. Optimizing parameters. Short methodology description.

The simulation will be done only for stationary design running loads. The boundary conditions being imposed, the optimization will pursue the following internal adimensional parameters, as entry data:

- The coefficient $\mathbf{k_{reh}=p_{reh}/p_0}$. Schroder [3] recommend $k_{reh} \in [0.22 \div 0.28]$. In this paper the interval $k_{reh} \in [0.2 \div 0.36]$ will be covered. Regarding the direct effect of k_{reh} variation on the investment, we mention that the growth of k_{reh} induce, through the rising of maximum extraction pressure and preheats pressure: **a)** the increase of feed water temperature and the augment of preheat line investments, respectively **b)** the growth in high and intermediate pressure turbine cylinders cases cost.
- The coefficient $\mathbf{k_{\Delta t}=\Delta t_{HPP\,n}/\Delta t_{LPP}}$, where $\Delta t_{HPP\,n}$ is the rise of temperature on the last HPP, supplied from the exit of high pressure cylinder, while Δt_{LPP} represent the equals growths into other stages. The paper [3] recommends $k_{\Delta t} \in [1.33 \div 1.8]$. In this paper the interval $k_{\Delta t} \in [0.6 \div 2]$ will be covered. The variation of $k_{\Delta t}$ does not have significant direct inferences on investments into water preheat line or steam turbine, but could having some indirect implications.

The next technical parameters will be following (note that their variations have direct influences on fixed and variable expenses):

- ***Global efficiency***, $\boldsymbol{\eta_{ea}=P_{bg}/P_{t1}}$ (P_{t1}=thermal energy flow rate at input into the cycle). The maximization of $\boldsymbol{\eta_{ea}}$ reduces the fuel expenses.
- ***The ratio between generator power and the main steam mass flow rate,*** $\boldsymbol{e_{sp\,0}=P_{bg}/D_0\,s}$, dimensional parameter. With P_{bg} in kW and $D_{0\,s}$=main steam mass flow rate in kg/s, it results $e_{sp\,0}$ in $kJ_{el}/kg_{main\ steam}$. The growth of $\boldsymbol{e_{sp\,0}}$ reduce investments into high pressure preheat feed water line, high pressure components of the boiler and main steam pipes.
- ***The ratio between generator power and the reheated steam mass flow rate,*** $\boldsymbol{e_{sp\,1}=P_{bg}/D_{1s}}$, ($D_{1\,s}$=reheated steam mass flow rate), dimensional parameter. The growth of $\boldsymbol{e_{sp\,1}}$ diminishes the price of intermediate pressure part of the boiler and reheated steam pipes.

The big numbers of variable and transcendent link equation obstruct the analytical study. The authors purpose a numerical simulation of given thermal schemes for well define sets of external parameters. We used existent methodologies and procedures internationally [4] and nationally validated, some of them conceived into our chair [5, 6, and 7].

The software has an iterative structure. We started from an imposed set of data, based on bibliography. The next steps will be following: **a)** steam turbine expansion process modeling; **b)** determining the thermal and mass flow rates on preheat line **c)** calculus of technical performances indicators, and **d)** recalculation of entry data. The model was applied and tested for a large scale of schemes and parameters[6]. In all situations it was precise and quickly convergent.

3. Presentation and preliminary interpretation of the obtained results.

Figures 3÷8 show the variation of $\boldsymbol{\eta_{ea}}$, $\boldsymbol{e_{sp\,0}}$, and, $\boldsymbol{e_{sp\,1}}$, versus k_{reh} and $k_{\Delta t}$, for the above mentioned schemes and parameters[7]. The better values of η_{ea}, $e_{sp\,0}$, and $e_{sp\,1}$ in scheme 8 4 comparing to 7 4 are caused firstly by the higher parameter at hot heat source and secondly by the scale effect. All situations have comparable variations. The results interpretation will take care of k_{reh} şi $k_{\Delta t}$ consequences on η_{ea}, $e_{sp\,0}$, and $e_{sp\,1}$, and those direct or indirect over the investment.

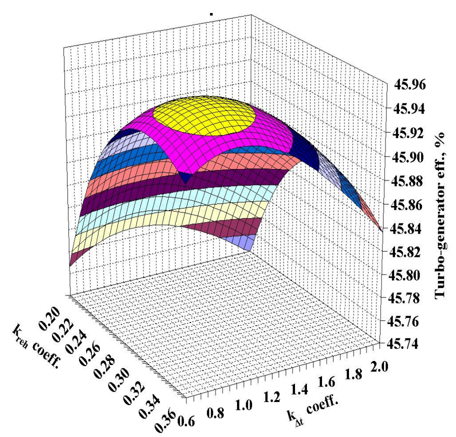

Fig. 3 η_{ea} versus $k_{\Delta t}$ and k_{reh}, for „7_4" scheme

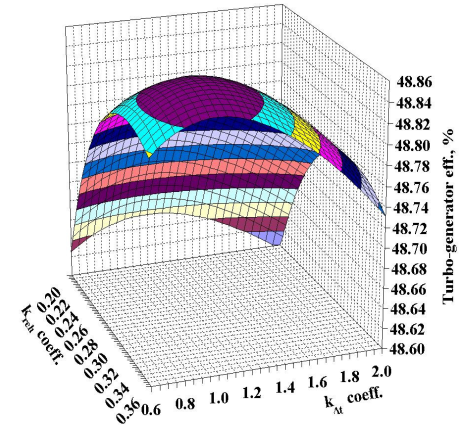

Fig. 4 η_{ea} versus $k_{\Delta t}$ and k_{reh}, for „8_4" scheme

Figures 3 and 4 point out that η_{ea} is a technical optimizing parameter; the surfaces describing the dependence on $k_{\Delta t}$ and k_{reh} having maximal values in the analyzed domain. In this way: **1)** η_{ea} maxim are reaching in the area $k_{reh} \in [0.31 \div 0.33]$ and $k_{\Delta t} \in [0.95 \div 1.05]$; **2)** η_{ea} minim is obtained on the border of the analyzed domain, in the points $k_{reh}=0.2$ and $k_{\Delta t}=2$. Standard deviations of the

[6] The domain described was covered in terms of size, main and reheated steam parameters. The condensing pressure, p_c, were choused in the interval $p_c \in [3.2 \div 6.4]$ kPa.

[7] The paper shows the results for extreme power sizes and hot source parameters. At the cold source we fixed p_c=4.5 kPa (t_c=31.1 °C), corresponding to mixed circuit cooling in Romania.

values are: about 0,107 % from $\eta_{ea\ med}$ in the scheme „7 4", respectively about 0,127 % from $\eta_{ea\ med}$ in the scheme „8 4". The differences between η_{ea} maxim and minim, reported at η_{ea} maxim, represent: circa 0.46 % from $\eta_{ea\ max\ 7\ 4}$ in the first scheme, and round about 0.54 % from $\eta_{ea\ max\ 8\ 4}$ in the second one. This indicates a relative flattening of the efficiency surfaces.

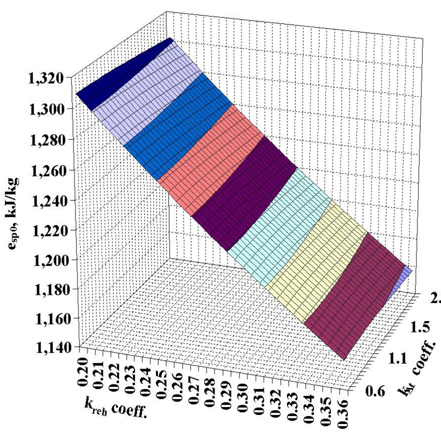

Fig. 5 $e_{sp\ 0}$ versus $k_{\Delta t}$ and k_{reh}, for „7_4" scheme

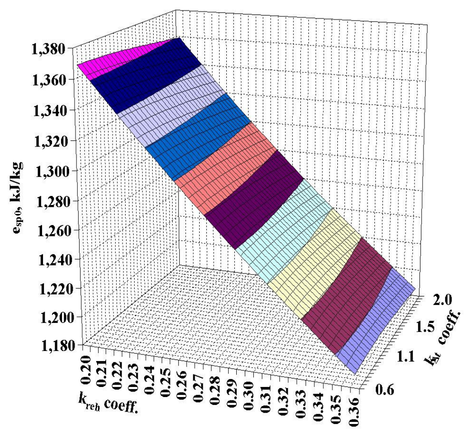

Fig. 6 $e_{sp\ 0}$ versus $k_{\Delta t}$ and k_{reh}, for „8_4" scheme

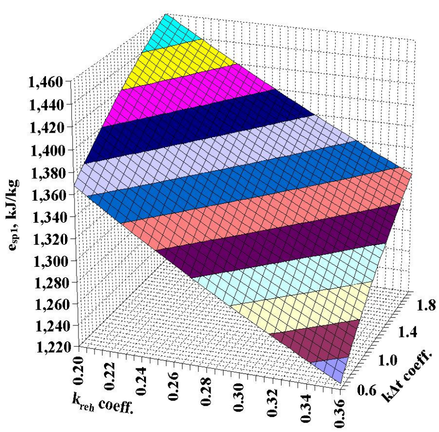

Fig. 7 $e_{sp\ 1}$ versus $k_{\Delta t}$ and k_{reh}, for „7_4" scheme

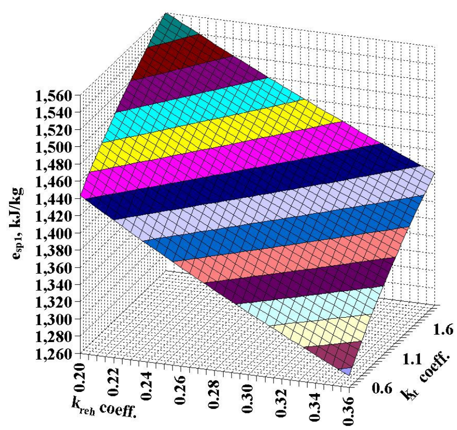

Fig. 8 $e_{sp\ 1}$ versus $k_{\Delta t}$ and k_{reh}, for „8_4" scheme

The surfaces representing $e_{sp\ 0}$ and $e_{sp\ 1}$ variation, function of k_{reh} and $k_{\Delta t}$ (fig. 5÷8) are almost flat with small curvatures. None of them have extreme values in the analyzed domain, but on the border. Maximal values are realized: **1)** for $e_{sp\ 0}$ in the point k_{reh}=0.2 and $k_{\Delta t}$=0.6, while **2)** for $e_{sp\ 1}$ in the point k_{reh}=0.2 and $k_{\Delta t}$=2. Minimal values are obtained in the other corners of the base surface: **1)** $e_{sp\ 0}$ in the point k_{reh}=0.36 and $k_{\Delta t}$=2, while **2)** for $e_{sp\ 1}$ in the point k_{reh}=0.36 and $k_{\Delta t}$=0.6.

Standard deviations for the analyzed values are: **1)** for $e_{sp\ 0}$ around 3.562 % from the average value, in the scheme „7 4", respectively circa 4.114 % from the average in the scheme „8 4”, and **2)** for $e_{sp\,1}$ around 3.687 % from $e_{sp\,0\,med}$ in the scheme „7 4”, respectively around 4.229 % from $e_{sp\,0\,med}$ in the scheme „8 4”. The differences between $e_{sp\,0}$ maxim and minim, reported at $e_{sp\,0}$ maxim, represent: **a)** around 11.73 % from $e_{sp\,0\,max\,7\,4}$ **i**n the first scheme, respectively **b)** 18.38 % from $e_{sp\,0\,max\,8\,4}$ in the second one.

We notice that the relative variation, function on k_{reh} and $k_{\Delta t}$, of $e_{sp\,0}$ and $e_{sp\,1}$, are bigger then those of η_{ea}. As well, the rate of variation of $e_{sp\,0}$ and $e_{sp\,1}$ after the two adimensional parameters are different:

- $e_{sp\,0}$ drops at k_{reh} increase, but varies a little function of $k_{\Delta t}$[8];
- $e_{sp\,1}$ drops at k_{reh} increase and raise at $k_{\Delta t}$ growth; the consequences on the both parameters are compatible and can mutually compensate.

4. Conclusions

For the analyzed schemes the consequences of k_{reh} and $k_{\Delta t}$ variation on η_{ea}, $e_{sp\,0}$, and $e_{sp\,1}$ indicators are contradictory (see table 1). Practically: **a)** there are not pairs of k_{reh} and $k_{\Delta t}$ that permit simultaneous maximization of, at least, two from three indicators and **b)** for o set of parameters that maximize one of the indicators, the other indicators are relatively remote of their maxim.

Table 1

The coordinates k_{reh} and $k_{\Delta t}$ for the extreme technical indicators (maxim / minim) and the extreme values associated

Indicator		η_{ea}		$e_{sp\,0}$		$e_{sp\,1}$	
Scheme		7 4	8 4	7 4	8 4	7 4	8 4
Mean values		45.889	48.781	1 229.60	1 273.12	1 349.02	1 425.65
Coordinates for maxim		k_{reh}=0.32; $k_{\Delta t}$=1		k_{reh}=0.2; $k_{\Delta t}$=0.6		k_{reh}=0.2; $k_{\Delta t}$=2	
Maximal Values	absolute	45,950	48,859	1.309,97	1.369,53	1.460,95	1.560,52
	% from mean	100.133	100.159	106.536	107.573	108.297	109.460
Coordinates for minim		k_{reh}=0.2; $k_{\Delta t}$=2		k_{reh}=0.36; $k_{\Delta t}$=0.2		k_{reh}=0.36; $k_{\Delta t}$=0.6	
Minimal Values	absolute	45.739	48.596	1 156.30	1 185.15	1 225.69	1 273.67
	% from max	99.539	99.462	88.270	86.537	83.897	81.618
	% from mean	99.671	99.620	94.039	93.091	90.857	89.340

In those conditions the optimal must be a multicriteria one. For selecting the quota of each parameter in the choice of optimal zone, we mention that:

- ✓ The influence of k_{reh} on all the three indicators is comparable. Because of that, the recommended value $k_{reh\,rec}$ can be obtained for equal quotas of the three indicators. Results $k_{reh\,rec}=(0.32*1+0.2*1+0.2*1)/3=0.24$.
- ✓ For choosing $k_{\Delta t}$, a smaller share for $k_{\Delta t}(e_{sp\,0\,max})$ is rational[9]. Function of

[8] Curves resulted by crossing the surface $e_{sp\,0}=f(k_{reh}\&k_{\Delta t})$ with vertical planes k_{reh}=ct. have a slight down concavity and achieve maximum values, or have trends to maximizing.
[9] The coefficient $k_{\Delta t}$ does not have greatly influence on $e_{sp\,0}$.

this share, we suggest two values for the indicator:

1. $k_{r\Delta t\ rec\ 1}$=(1*1+0.6*0.25+2*1)/2.25=1.4.
2. $k_{r\Delta t\ rec\ 2}$=(1*1+0.6*0+2*1)/2=1.5.

The values obtained in the two situations are shown in table 2.

Table 2

Technical indicators for the optimal area: k_{reh}=0.24 & $k_{\Delta t} \in 1.4 \div 1.5$

Indicator		η_{ea}		$e_{sp\ 0}$		$e_{sp\ 1}$	
Scheme		74	84	74	84	74	84
Values for optimal 1	Absolute	45.877	48.761	1 265.46	1 316.04	1 390.63	1 475.52
	% from maxim	99.841	99.801	96.602	96.094	95.187	94.554
	% from average	99.974	99.960	102.916	103.371	103.085	103.498
	% from minim	100.303	100.340	109.440	111.044	113.458	115.848
Values for optimal 2	Absolute	45.871	48.754	1,264.84	1,315.23	1,397.07	1,483.66
	% from maxim	99.827	99.786	96.555	96.035	95.628	95.075
	% from average	99.959	99.945	102.866	103.308	103.562	104.069
	% from minim	100.289	100.326	109.386	110.975	113.983	116.487

We observe a good technical and economical compromise in the sense that, for the recommended values:

- The realized efficiencies are similar with the middling values on the analyzed domain and represent around 99.8 % from the peak. Decreasing k_{reh} from 0.32 to 0.24, combined with the growth of $k_{\Delta t}$ from 1 to 1.4÷1.5 ($k_{\Delta t}$=1 and k_{reh}=0.32 being the optimal couple from the η_{ea} point of view), increase with only 0.2 % the fuel spends in report with minimal ones.
- The specific energies for 1 kg of main steam are 103 % from the average ones and represent 96 % from the maximal ones.
- The specific energies for 1 kg of reheated steam are around 104 % from the average ones and represent over 95 % from the maximal ones.

For a simplified economical analysis, we consider that the investments in pipes and heat exchangers are directly proportional with the mass steam flow rate. We appreciate the following:

- The growth of k_{reh} from 0.2 to 0.24 and of $k_{\Delta t}$ from 0.6 to 1.4 (k_{reh}=0.2 and $k_{\Delta t}$=0.6 is the optimal value from $e_{sp\ 0}$ point of view) have the next consequences on the investment in the high pressure feed water preheat line, high pressure boiler part, and main steam pipes: **a)** growth with 3%reported to minimal investment; **b)** reduction with over 5% from the investments necessary for the efficiency optimal pair k_{reh} & $k_{\Delta t}$.
- The growth of k_{reh} from 0.2 to 0.24 and decrease of $k_{\Delta t}$ from 2 to 1.4 (k_{reh}=0.2 and $k_{\Delta t}$=2 is the optimal set from $e_{sp\ 1}$ point of view) have the next consequences on the investment into intermediate pressure boiler, reheated hot and could main steam pips, and high and intermediate pressure steam turbine cylinders: **a)** growth with around 4 % in report with

minimal; **b)** reduction with over 5% from the investment for maximal η_{ea}.

On the whole, we appreciate that the efficiency sacrifice of around 0.2 % might be compensated by the reduction of at least 3.5 % of spends in high pressure water preheat line, high and intermediate pressure boiler part, high and intermediate steam pressure pipes, and high and intermediary steam turbine cylinders. Those can justify choose of k_{reh}=0.24; $k_{\Delta t} \in 1.4 \div 1.5$ area, even if in this area none of the followed indicators is maximizing.

Obtained results are in concordance with the recommendation from the literature [2, 3, 5, 6, and 8]. In the future, the authors intend doing the same kind of analyses for smaller steam units, with subcritical pressure and simplified water preheat scheme.

We consider that the results obtained in this paper are useful for the design of new high power conventional steam power units, and repowering the existing ones. In order to develop the analyses, more data regarding **a)** fuel and heat cost, **b)** spends share into investments, and c) the influence of standard components use on the unit's investment cost, will be necessaries.

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