CORRELATIVELY OPTIMIZING THE REHEAT PRESSURE AND THE REGENERATIVE PREHEAT LINE TEMPERATURE GROWTH'S REPARTITION, FOR USC HIGH POWER TPP UNITS

Victor - Eduard CENUŞĂ[1], Florin - Niculae ALEXE[2], Horia - Ionuț PETCU[3]

The paper refers to high power ST TPP with elevated steam parameters, single reheat, and advanced feed water preheat, having a steam extraction in turbine's HPC. It pursues simultaneous technical optimization of: ***1)*** *steam reheat pressure, and* ***2)*** *temperature's growth repartition between preheating stages. The study is done by numerical simulation. The results identify an interest area zone, showing that is impossible, in the same time:* ***a)*** *minimizing the fuel expenses,* ***b)*** *satisfying technical restrictions, and* ***c)*** *reducing investment. We suggest a low efficiency sacrifice, compensated by an investment reduction with at least 3.5 % .*

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

1. Introduction, objectives, assumptions and methods

The paper follows the thermodynamic optimization, taking into consideration technical restrictions and economic consideration, of Steam Turbines Thermal Power Plants (ST TPP) high power unit's.

The primaries methods for cycle's efficiency increase are based on growing extreme (max. vs. min.) cycles parameters difference. A second way, by "carnotization", refers to "internal" parameters:

- 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), feed water temperature, preheat repartition by stages, etc.

In practice these improving methods are simultaneous and correlated applied. For non-reheat cycles it is generally accepted [1 to 4] that the peak thermal efficiency is obtained for equals temperature's growths in feed water preheat stages. In single reheat cycles with no steam extraction in turbine's High Pressure Cylinder (HPC), many papers [4 to 6] recommend choosing a bigger temperature growth in the final preheat stage, supplied with steam extracted

---

[1] As. Prof. PhD, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania

[2] Prof. PhD, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania

[3] As. PhD, Power Engineering Faculty, University "Politehnica" of Bucharest, Romania

amount of reheat.

Our paper analyze high power unit's ST TPP cycles, with Ultra Super Critical (USC) main steam parameters and advanced feed water preheat, having a steam extraction during the steam's expansion in turbine's HPC. It pursues simultaneous technical optimization of: **1)** steam reheat pressure, and **2)** temperature's growth distribution between feed water preheating stages. In the same time we follow if the thermodynamically optimal solution can satisfy the main technical and economical restrictions.

The assumptions for thermal scheme generating are [7 to 9]: **A.** The surface Low Pressure Preheaters (LPP) number should be greater than, or at least equal to, the number of HPP. **B.** The Deaerator (D), having sliding pressure, must not use steam from the first extraction behind the reheat. Therefore the minimum number of High Pressure Preheaters (HPP) is three. **C.** The preheat stages supplied with steam after the reheat, will have equal temperature growths. **D.** The main feed water pumps will be drive by condensing steam turbines. **E.** The HPP supplied with steam from the first extraction after the reheat, will have a separate heat transfer surface mounted after the last HPP. Fig. 1 shows such a scheme with z_{st}=8 water preheating stages (4 LPP+1 D+3 HPP).

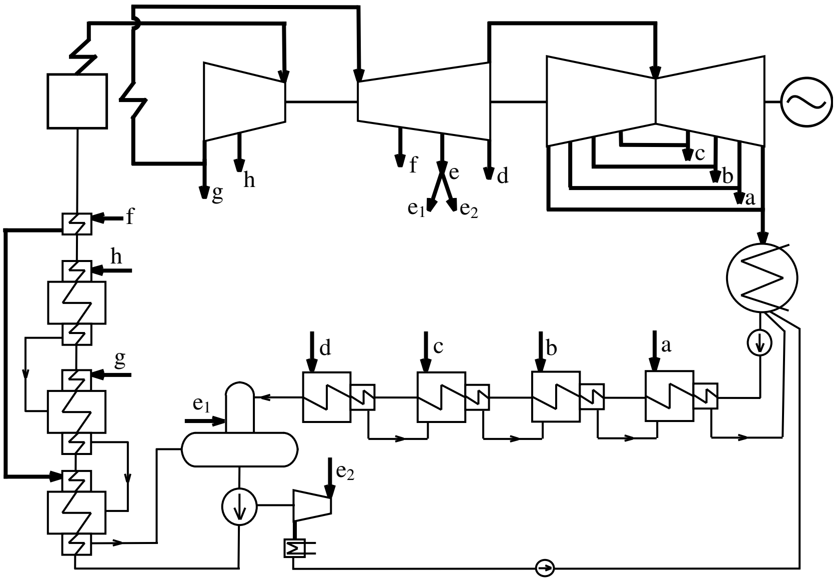


Fig. 1. Design scheme

Because of design's complexity, variables number, and transcendent equation, the study is done through numerical simulation performed only for stationary design loads. Our software, using validated methodologies, functions [10], and procedures, most of them conceived and in our chair [11, 12], have an iterative structure. We started from an imposed set of data, based on bibliography. The next steps are the 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 calculus restarts with the obtained results, continuing until the error is enough small. The model was tested on a large scale of schemes and parameters. In al circumstances it was precise and quickly convergent.

The outer boundary conditions being imposed, the inner adimensional parameters in use as entry data for comparatively investigation are:

- $\mathbf{k_{reh}=p_{reh}/p_0 \in [0.2 \div 0.32]}$, where p_{reh} is the reheat pressure.
- $\mathbf{k_{\Delta t}=\Delta t_{HPP\#7}/\Delta t_{LPP} \in [0.6 \div 1.8]}$, where $\Delta t_{HPP\#7}=\Delta t_{HPP\#8}$ is the rise of temperature in HPP supplied with steam amount of reheat, and Δt_{LPP} is the equals growths into other stages ($LPP_{\#1\ to\ 4}$, Deaerator, and $HPP_{\#6}$).

The main pursued output data, having influences on technical feasibility and on fixed and/or variable TPP's expenses, are the followings:

- The global turbine & generator efficiency, $\boldsymbol{\eta_{ea}=P_{bg}/P_{t1}}$ (P_{bg}=power at generator clams, and P_{t1}=thermal energy flow rate at the hot source). Optimizing $\boldsymbol{\eta_{ea}}$ reduces the fuel expenses.
- The adimensional ratio between higher extraction pressure ($p_{extr\ h}$) and main steam pressure (p_0) $\boldsymbol{k_{HP\ extr}}$. This one is limited by equipment's technical feasibility reasons.
- The ratio between P_{bg} and the main steam mass flow rate ($D_{0\ s}$), $\boldsymbol{e_{sp\ 0}=P_{bg}/D_{0\ s}}$, dimensional parameter (with P_{bg} in kW and $D_{0\ s}$ in kg/s, it results $e_{sp\ 0}$ in $kJ_{\ el}/kg_{\ main\ steam}$). Rising $\boldsymbol{e_{sp\ 0}}$ reduces investments into high pressure components.
- ***The ratio between P_{bg} and the reheated steam mass flow rate*** $D_{1\ s}$, $\boldsymbol{e_{sp\ 1}=P_{bg}/D_{1s}}$, dimensional parameter in $kJ_{\ el}/kg_{\ reheated\ steam}$. Growing $\boldsymbol{e_{sp\ 1}}$ diminishes the price of intermediate pressure parts.

We used a wide range of input data, size ($P_{bg} \in [640 \div 1000]$ MW), and steam parameters ($p_0 \in [24 \div 32]$ MPa, $t_0/t_{reh} \in [550 \div 620]$ °C, $p_c \in [3.2 \div 6.4]$ kPa).

2. Presentation and preliminary interpretation of the obtained results

Because adimensional input data where utilized, and the output data are ratios, the obtained results are similar for all above mentioned input data. We show and comment the results for P_{bg}=800 MW, p_0=32 MPa, t_0=600 °C, t_{reh}=620 °C, and p_c=4.5 kPa. The results interpretation will take especially 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. Related to p_h/p_0 ratio, its values influence only the field of acceptable pair of parameters k_{reh} and $k_{\Delta t}$, in order to respect the equipment's technical feasibility reasons.

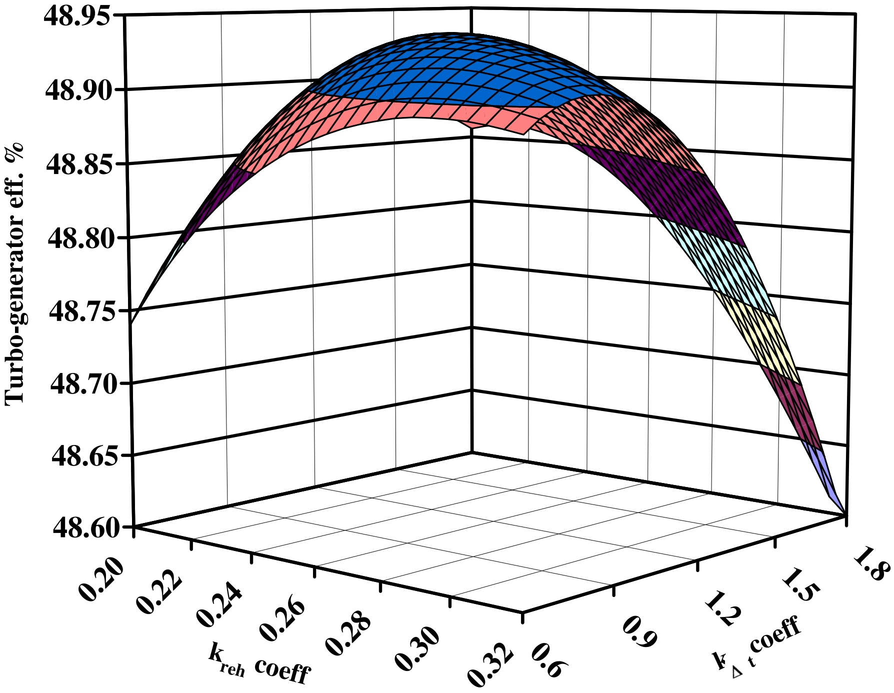


Fig. 2. η_{ea} versus $k_{\Delta t}$ and k_{reh}

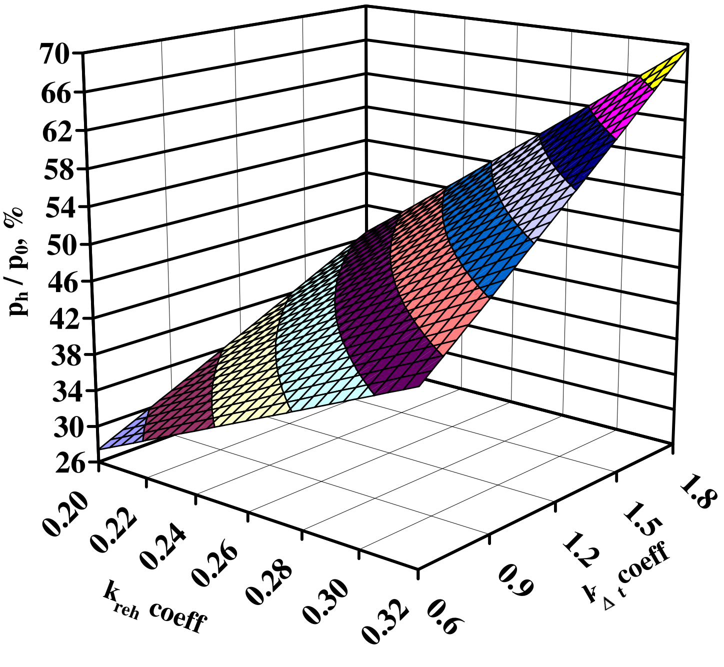


Fig. 3. p_h/p_0 versus $k_{\Delta t}$ and k_{reh}

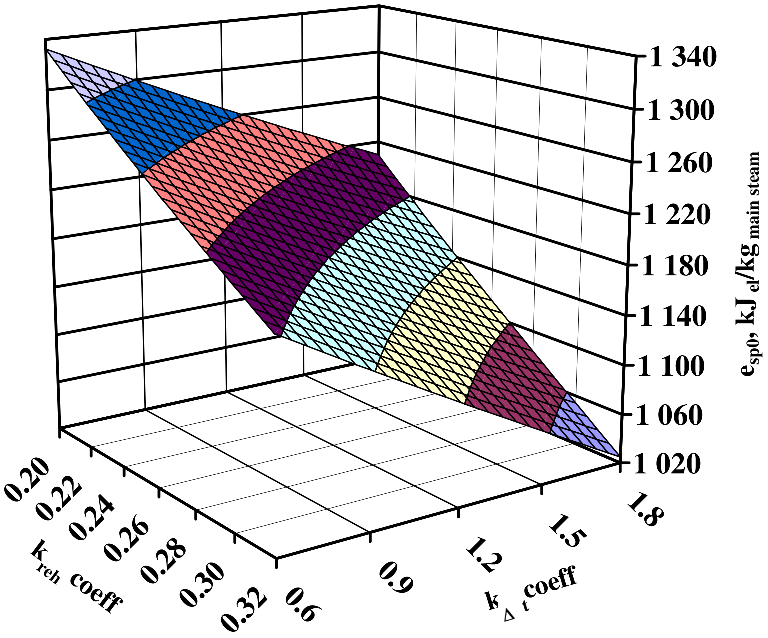


Fig. 4. $e_{sp\,0}$ versus $k_{\Delta t}$ and k_{reh}

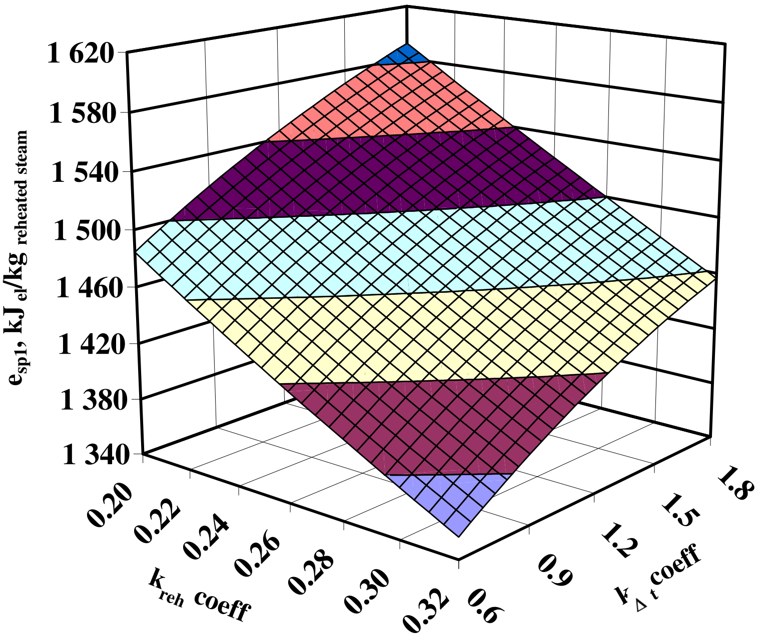


Fig. 5. $e_{sp\,1}$ versus $k_{\Delta t}$ and k_{reh}

Fig. 2 shows the variation of $\boldsymbol{\eta_{ea}}$ versus k_{reh} and $k_{\Delta t}$, indicating that η_{ea} is a technical optimizing parameter. The surfaces showing their dependence on $k_{\Delta t}$ and k_{reh} have a peak values, minimizing the fuel expenses, for $k_{reh} \in [0.255 \div 0.265]$ and $k_{\Delta t} \in [1 \div 1.1]$, equivalent to almost equal HPP temperature growths. The η_{ea} minim is obtained on the domain's border. Standard deviation of relative values is small: $\sigma_{rel}(\eta_{ea}) = \pm 0.1235$ % from $\eta_{ea\ med}$. This indicates a relative flattening of the efficiency surface.

Figures 3, 4, and 5 show the variation of $\boldsymbol{k_{HP\ extr}}$, $\boldsymbol{e_{sp\ 0}}$, and, $\boldsymbol{e_{sp\ 1}}$, versus k_{reh} and $k_{\Delta t}$. The surfaces representing their variation, function of k_{reh} and $k_{\Delta t}$ are almost flat with small curvatures. None of them have extreme values in the analyzed domain, but on the border. All of these indicators:

1) have larger variations: $\sigma_{rel}(k_{HP\ extr}) = \pm 19.67$ from $k_{HP\ extr\ med}$, $\sigma_{rel}(e_{sp\ 0}) = \pm 5.525$ from $e_{sp\ 0\ med}$, and $\sigma_{rel}(e_{sp\ 1}) = \pm 3.42$ from $e_{sp\ 1\ med}$,

2) are always descending or rising with k_{reh} and $k_{\Delta t}$.

These results demonstrate that, for the analyzed scheme, is impossible, in the same time: **a)** minimizing the fuel expenses, **b)** satisfying the technical feasibility restriction $k_{HP\ extr} \leq 40$ %, and **c)** reducing the investment.

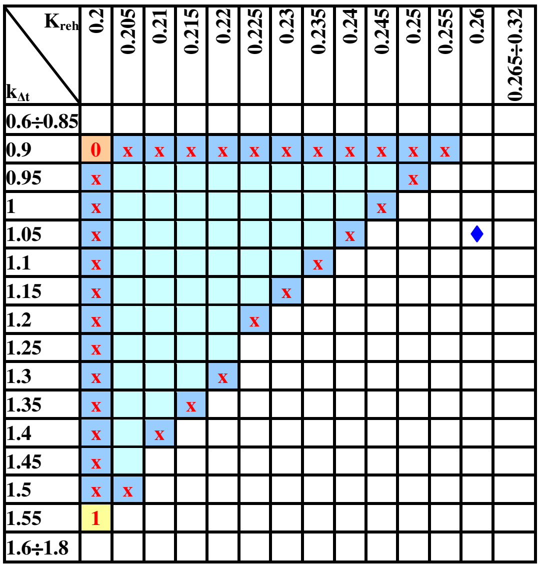
3. Conclusions

The consequences of k_{reh} and $k_{\Delta t}$ variation on η_{ea}, $e_{sp\ 0}$, and $e_{sp\ 1}$ indicators are contradictory. Practically: **a)** there are not pairs of k_{reh} and $k_{\Delta t}$ that permit simultaneous maximization of, at least, two from those three indicators and **b)** for a set of parameters that maximize one of the indicators, the other indicators are relatively remote of their maxim. 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 $k_{\Delta t}$; 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;
- $e_{sp\ 1}$ drops at k_{reh} increase and raise at $k_{\Delta t}$ growth.

The effects on the latest two parameters are compatible and can be mutually compensate.

In those conditions the optimal must be a multicriteria one. We observe that the pair k_{reh} and $k_{\Delta t}$, for η_{ea} maximizing, is: **1)** far from the points where are maximizing $e_{sp\ 0}$ ($k_{reh} \cong 0.2$, $k_{\Delta t} \cong 0.6$) and $e_{sp\ 1}$ ($k_{reh} \cong 0.2$, $k_{\Delta t} \cong 1.8$), respectively **2)** outside the limits imposed by the technical restriction $k_{HP\ extr} \leq 40$ %. Fig. 6 identifies the interest zone for a correlatively optimization: $0.9 \leq k_{\Delta t} \leq 1.55$, $k_{HP\ extr} \leq 40$ %. In order to respect the latest restriction, and to diminish in the same time $e_{sp\,0}$ and $e_{sp\,1}$, respectively to fall the investment's costs, it seems rationally choosing a value of k_{reh} lower than the thermodynamically optimal one, and proper values of $k_{\Delta t}$, so bigger temperature growth for the final preheat stages.



$k_{\Delta t}$ \ K_{reh}	0.2	0.205	0.21	0.215	0.22	0.225	0.23	0.235	0.24	0.245	0.25	0.255	0.26	0.265÷0.32
0.6÷0.85														
0.9	0	x	x	x	x	x	x	x	x	x	x	x		
0.95	x										x			
1	x									x				
1.05	x								x				♦	
1.1	x							x						
1.15	x						x							
1.2	x					x								
1.25	x													
1.3	x				x									
1.35	x			x										
1.4	x		x											
1.45	x													
1.5	x	x												
1.55	1													
1.6÷1.8														

♦	**Maximal turbogenerator efficiency**
x	**Limits of technical interest area**
0	**Point of maximal $e_{sp\,0}$ in the interest area**
1	**Point of maximal $e_{sp\,1}$ in the interest area**

Fig. 6. Interest area zone

We suggest a technical and economical compromise, appreciating that an efficiency sacrifice of less than 0.1 % might be compensated by the reduction of at least 3.5 % of investment in: **a)** high pressure water preheating line, **b)** high and intermediate pressure boiler part, **c)** high and intermediate steam pressure pipes, and **d)** high and intermediary steam turbine's cylinders. Those can justify choosing $k_{reh} \leq 22.5$ %, and $k_{\Delta t} \cong 1.15 \div 1.2$.

In a future article we will complete the analysis with economical considerations and calculations, starting from the technical results obtained in this document.

REFERENCES

[1]. *L. Musil,* Gesamtplanung von Dampfturbinenkraftwerken, Springer, Berlin, 1942.
[2]. *P. Kiameh*, Power Generation Handbook, McGraw-Hill, New York, 2002.
[3]. *R.E. Sonntag, C. Borgnakke and G.J. Van Wylen*, Fundamentals of thermodynamics, J. Wiley and Sons Inc., New York, 2003.
[4]. *K. Schroder,* Grosse Dampfkraftwerke, Vol II, Springer, Berlin, 1962.
[5]. *K. Schroder,* Grosse Dampfkraftwerke, Vol III, Springer, Berlin, 1966.
[6]. *F. Alexe, V. Cenuşă and H. Petcu*, Optimizarea preîncălzirii regenerative şi supraîncălzirii intermediare la I.T.A. din C.T.E. (Optimizing the regenerative feed water preheat and the reheat pressure for TPP's steam turbines), in Revista Energetica, Bucharest, no. 2,

February, 2009, pp. 89–96.

[7]. *C. Moţoiu,* Centrale Termo şi Hidro Electrice (Thermal and Hydro Power Plants), Editura Didactică şi Pedagogică, Bucharest, 1974

[8]. *I.G. Carabogdan, & others,* Manualul Inginerului Termo Energetician Vol. 3 (Thermal Power Engineering Handbook, Tome III), Editura Tehnică, Bucharest, 1983

[9]. *D.C. Ionescu, G. Darie, A.P. Ulmeanu and V. Cenuşă*, Centrale Termoelectrice Performante (Efficient Thermal Power Plants), AGIR, Bucharest, 2006.

[10]. *B. Spang*, Equation of IAPWS-IF97, http://www.cheresources.com

[11]. *V. Cenuşă, F. Alexe,* "Optimizarea ciclurilor termice ale CET urbane moderne cu ITA" (Optimal thermal cycle of Urban CHP Units), in Revista Energetica, Bucharest, no. 5, May, 2008, pp. 197–200.

[12]. *F.N. Alexe, V.E. Cenuşă*, „Correlatively optimizing the regenerative feed water preheat and the reheat parameters for condensing steam cycles", in Buletinul Institutului Politehnic din Iasi, Electrotehnica, Energetica, Electronica, **Vol. LIV (LVIII)**, no. 3, 2008, pp. 511–518.