Thermodynamic Analyses for Optimizing the Design of HTGR's Helium Brayton Cycles

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Abstract: - The paper analyzes the close-circuit Brayton (Joule) cycles for High Temperature Gas (Helium) cooled nuclear Reactors (HTGR). Analyzed cycles are with Regenerative Heat Exchanger (RHE), Fragmented Compression and Inter-Cooling (FC&IC). The HTGR imposes the working agent and hot source's parameters. The cooling conditions give the cycle's minimal temperature. In the 1st paper's section, for ideal processes cycles, we show that: ***A)*** the boundary parameters and design schemes inflict: ***A₁)*** the compression ratios (ε), ***A₂)*** the specific net work per 1 kg He (w_{net}), and ***A₃)*** the thermal efficiencies (η_{th}); ***B)*** the performances are increasing with the IC's number. In the 2nd section we are taking into consideration the irreversibility's factors (temperature difference at RHE, revolving machines isentropic efficiencies, and pressure drops) doing sensitivity analyses about their influences on real processes cycle's performances. We show that: ***1)*** cycle's performances are not continuous growing with IC's number, and ***2)*** the main influences on design's option are given by: ***2_1)*** the temperature difference at RHE and ***2_2)*** the pressure drops. In the 3rd section we adjusted all the quality factors in a similar manner, reducing the irreversibilities, showing the synergic influences. The 4th section relaxes the hot source's restrictions. It analyses the influence of HTGR output / input temperatures variation on the main thermodynamic data, showing: ***α)*** the benefit of maximal temperature increase and ***β)*** the need to correlate HTGR's temperature increment output vs. input with the maximal temperature. The final section contains the main conclusions of the paper.

Key-Words: - Brayton Cycle, HTGR, Irreversibility, Sensitivity Analysis, Numerical Computation, and Thermodynamic Optimization.

1 Introduction. Problem Formulation

The paper analyses the performances of single loop close circuit Brayton cycle, using HTGR as hot source. The closed cycle allows using: ***1)*** a clean working agent, with advantageous properties; ***2)*** work pressures not depending from the atmospheric one [1 to 4]. Helium's use in thermodynamic circuits offers the following advantages [1, 2, and 5]: ***a)*** it performs as an ideal gas; ***b)*** it has a big heating capacity per kg; ***c)*** the big sound velocity allows rising the compression and expansion ratios per compressor's / turbine's stages; ***d)*** the small viscosity leads to low pressure drops; ***e)*** linked with the elevated thermal conductivity it leads to high heat exchange coefficients. For HTGR it is also important the fact that Helium is chemically and radiological inert.

The HTGR imposes: **I)** the working fluid, **II)** the hot source inlet/output parameters. The cooling conditions give the cycle's minimal temperature. In a previous paper [4] we analyzed the ideal processes cycles on this kind of boundary conditions.

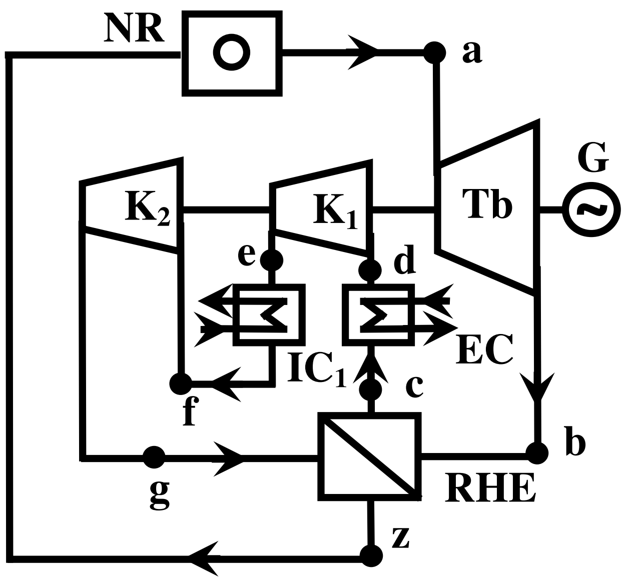

Fig.1 Brayton cycle with RHE, FC and $n_{IC\ stages}$=1

Our results where showing the low performances of simple cycle, without or with RHE. We continue the analysis only for cycles with RHE, FC&IC (see fig. 1 and 2), starting with ideal processes cycles and continuing with the real processes ones.

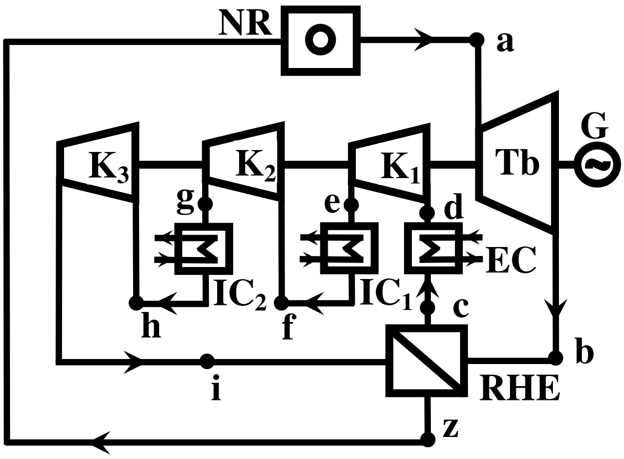

Fig.2 Brayton cycle with RHE, FC and $n_{IC\ stages}$=2

The targets are to envisage the thermodynamic performances of ideal and real processes cycles, in both designs, and to determine the influence of different input data on these performances, in order to choose the optimal design.

2 Analytical Approach

2.1 Ideal processes cycles

In both designs we fixed the hot source's input/output temperatures T_a/T_z. In order to have the same temperatures at turbine's output and NR's input ($T_b=T_z$), and knowing the Helium's isentropic coefficient (γ), the turbine's expansion ratio (ε_T), equal with the compression one (ε_K), is [5, and 6]:

$$\varepsilon_T = (p_a/p_z) = (T_a/T_z)^{\gamma/(\gamma-1)} = \varepsilon_K \qquad (1)$$

At the cold source, we considered the same minimal Helium's temperatures at External Cooler (EC) and IC outputs:

$$T_d=T_f=T_h \qquad (2)$$

It is generally accepted [5 to 7] that for FC&IC it is recommendable to equal allocate the compression between stages. The values are depending on inter-cooling stage's number (n_{IC}):

$$\varepsilon_{K\ t\ stage} = \sqrt[(n_{IC}+1)]{(p_a/p_b} = \left(T_a/T_b\right)^{\frac{\gamma}{(n_{IC}+1)\cdot(\gamma-1)}} \qquad (3)$$

The temperatures at EC and IC output's are:

$$T_e = T_g = T_i = T_d \cdot \left(T_a/T_z\right)^{[1/(n_{IC}+1)]} \qquad (4)$$

The general equation for determining the η_{th} of ideal processes RHE, FC and IC cycles became:

$$\eta_t = [(T_a - T_z) - (n_{IC}+1)(T_e - T_d)]/(T_a - T_z) = \\ = 1 - \frac{T_y}{T_z}\cdot(n_{IC}+1)\cdot\frac{\left(T_a/T_z\right)^{\frac{1}{n_{IC}+1}} - 1}{(T_a/T_z) - 1} \qquad (5)$$

It show that, if $n_{IC}\to\infty$, the cold source's process became isotherm, and it's average temperature (T_{csa}), became equal with the minimal one: $T_{csa}=T_d=T_f=T_h$ (see fig. 3, representing in T-s coordinates the processes in an ideal cycle with n_{IC}=2). Conventionally, the technical entropy was considered s_0=0 for p_{ref}=10 MPa, respectively T_{ref}=273.15 K (0 °C).

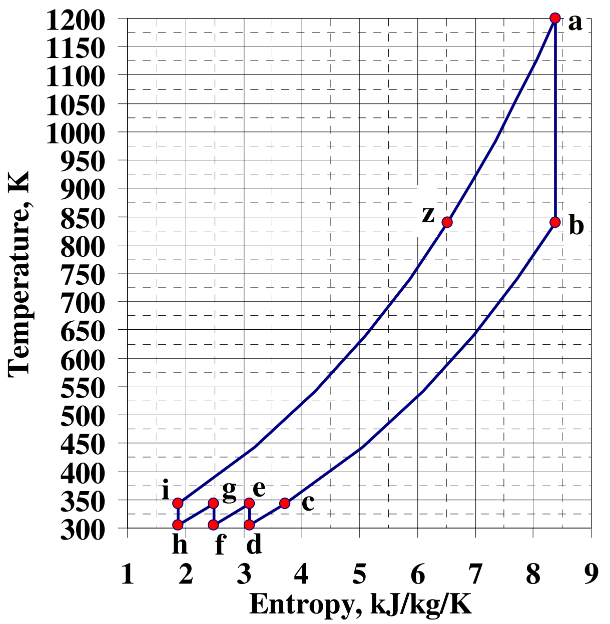

Fig. 3 T-s diagram of an ideal processes cycle with RHE&FC, with n_{IC}=2 (fig. 2 design)

The middle hot source's temperature (T_{hsa}), could be determined as a logarithmic average:

$$T_{hsa} = (T_a - T_z)/\ln\left(T_a/T_z\right) \qquad (6)$$

The maximal thermal efficiency, allowing fully using the hot source's exergetic potential [5 to 7], is:

$$\eta_{max\ t\ (IC=\infty)} = 1 - T_y\cdot[\ln\left(T_a/T_z\right)]/(T_a - T_z) \qquad (7)$$

2.2. Real Processes Cycles.

We continue to consider Helium as ideal gas, but we are taking into account the processes irreversibility [5 to 9], due to:

a) The temperature difference, characterizing the exergetic degradations by heat exchange into RHE, ΔT, same at the warm and cold ends:

$$\Delta T = (T_b - T_{z)}) = (T_c - T_g)_{n_{IC=1}} = (T_c - T_i)_{n_{IC=2}} \qquad (8)$$

b) The entropy grows in the compressors and turbine's processes. They are computed starting from isentropic efficiencies:

$\eta_{is\ T}$ $\quad \eta_{is\ T} = (T_a - T_{b\ real})/(T_a - T_{b\ theoretic})$ (9)

$$\eta_{is\ K} = (T_{e\ theoretic} - T_d)/(T_{e\ real} - T_d) \quad (10)$$

c) The relatively pressure drops in NR, RHE, EC, IC, and pipes. With the notation:

$$\Delta p_{rel} = (p_{output} - p_{input}) \Big/ \sqrt{p_{input} \cdot p_{output}} \quad (11)$$

the improper fraction for pressure drops R is:

$$R = (p_{output} / p_{input}) = \{2/[\sqrt{(4+\Delta p_{rel}^2)} - \Delta p_{rel}]\}^2 \quad (12)$$

For real processes cycles with RHE, FC&IC, the turbine's real output temperature ($T_{b\ r}$) should be with ΔT bigger than the NR input one:

$$T_{b\ r} = T_z + \Delta T \quad (13)$$

The turbine's theoretic outlet temperature is:

$$T_{b\ t} = T_a - (T_a - T_z - \Delta T)/\eta_{is\ Tb} \quad (14)$$

We obtain the turbine's real expansion ratio:

$$\varepsilon_{Tb\ r} = \{T_a \big/ [T_a - (T_a - T_z - \Delta t)/\eta_{is\ Tb}]\}^{[\gamma/(\gamma-1)]} \quad (15)$$

Considering the same relatively pressure drops for NR, RHE, EC, and IC:

$$R_{RN} = R_{RHE} = R_{EC} = R_{IC} = R \quad (16)$$

we obtain the global compression fraction (define as a ratio between the last stage output pressure and the first stage input pressure):

$$\varepsilon_{K\ r\ gl} = p_g / p_d = p_i / p_d = \varepsilon_{Tb\ r} \cdot R^{3+n_{IC}} \quad (17)$$

The identical compression ratios per one stage will depend on: ***a)*** relatively pressure drops on IC, and ***b)*** the IC number:

$$\varepsilon_{K\ r\ stage} = \sqrt[(n_{IC}+1)]{\varepsilon_{K\ r\ global} \cdot R^{n_{IC}}} \quad (18)$$

It allows calculating the compressors outlet real temperatures:

$$T_e = T_g = T_i = T_d \cdot [1 + (\varepsilon_{K\ stage}^{(\gamma-1)/\gamma} - 1)/\eta_{is\ K}] \quad (19)$$

For low pressure Helium, the RHE's output / EC's input temperature should be bigger with ΔT than the last compressor's output one:

$$T_c = T_d \cdot [1 + (\varepsilon_{K\ stage}^{(\gamma-1)/\gamma} - 1)/\eta_{is\ K}] + \Delta T \quad (20)$$

Finally we are determining the work and heat exchanges for each process, and the real thermal efficiencies of analyzed cycles.

3 Numerical Solution for Given Data

The main conclusion of real cycle's analysis is that the boundary restrictions on NR and cold source, cumulated with data describing the irreversibility ($\eta_{is\ K}$, $\eta_{is\ T}$, ΔT, and Δp_{rel}), leads for each scheme at imposed values of: **1)** expansion / compression ratios, and **2)** real thermal efficiencies. It is difficult and irrelevant comparing the performances of different designs only on formulas. We did computations with a typical set of input data [1, 2]:

- ✯ For the RN we have: p_z=7.2 MPa, T_z=840 K (566.85 °C), T_a=1.200 K (986.85 °C).
- ✯ For the cold source, T_d=T_f=T_h=305 K (31.85 °C), is restricted by the cooling water temperature.
- ✯ For characterizing the irreversibility we considered: **a)** $\Delta T_{RHE\ ref}$=35 K, as a fraction from the geometric average cycle's temperature, see relation (17), **b)** $\eta_{is\ K\ ref}$=$\eta_{is\ T\ ref}$=0.91, respectively **c)** $\Delta p_{rel\ ref}$=3.16 % (R=p_{output}/p_{input}=1.03213).

$$\Delta T_{HRE\ ref} = (1/16) \cdot \sqrt{T_{hsa} \cdot T_d} \cong 0.063 \cdot \sqrt{T_{hsa} \cdot T_d} \quad (21)$$

The main results, given in table 1, show that the efficiency increase is very low, when n_{IC} go up from n_{IC}=1 to n_{IC}=2. We did computation and for n_{IC}=3 [4], showing that η_{th} is lower than for n_{IC}=2.

Table 1. Numerical values characterizing the analyzed cycle's performances

No	Data	MU	Notation	n_{IC}=1	n_{IC}=2	Average
1	Number of compressor's stages	-	n_K	2	3	-
2	Number of inter-cooling stages	-	n_{IC}	1	2	-
3	Primary heat at source	kJ/kg	q_{NR}	1,871.1		
4	Global compression ratio	-	$\varepsilon_{K\ r\ gl}$	2.8383	2.9306	***2.8840***
5	Compression ratio per stage	-	$\varepsilon_{Kr\ stage}$	1.6847	1.4310	1.5527
6	Turbine's expansion ratio	-	ε_{Tb}	2.4186		
7	Turbine's generated mechanical work	kJ/kg	w_{Tb}	***1,689.19***		
8	Compressor's consumed mechanical work	kJ/kg	w_K	808.29	805.56	***806.93***
9	Compressor mechanical work (relatively to turbine)	%	w_K/w_{Tb}	47.851	47.689	47.770
10	Net mechanical work (at revolving machines shift)	kJ/kg	$w_{net}=w_{Tb}-w_K$	880.89	883.62	882.26
11	Regenerate heat in RHE	kJ/kg	q_{RHE}	2,376.5	2,512.1	***2,444.3***
12	Quota of regenerate heat (relatively to primary heat)	-	q_{RHE}/q_{NR}	127.01	134.26	130.64
13	Waste heat at cold source	kJ/kg	q_{EC}	990.21	987.48	988.84
14	Thermal cycle efficiency	%	η_{th}	47.079	47.225	***47.152***
15	Thermal cycle efficiency versus maximum theoretic one	%	η_{th}/η_{max}	67.466	67.675	67.571

It results that, for these input data, the thermodynamic optimal design require $n_{IC}=2$.

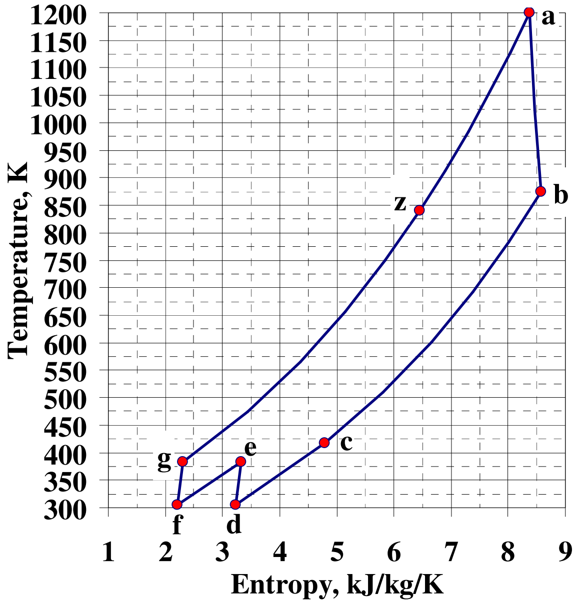

Fig. 4 T-s diagram of real processes in RHE, FC&IC cycle, with $n_{IC}=1$ (fig. 1 design)

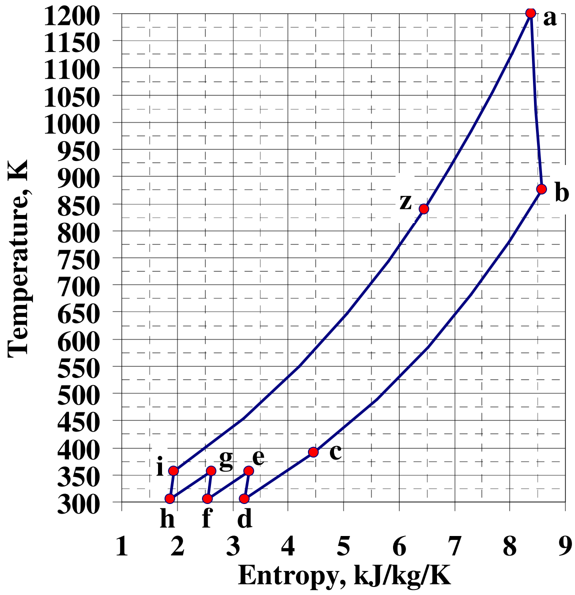

Fig. 5 T-s diagram of real processes in RHE, FC&IC cycle, with $n_{IC}=2$ (fig. 2 design)

Using the results we build fig. 4 and fig. 5, representing the processes in real cycles, for both of technical interesting designs, in T-s coordinates.

4 Sensitivity Analyses

The verdict that the efficiency augment is low when n_{IC} ascend from $n_{IC}=1$ to $n_{IC}=2$, and becomes lower for $n_{IC}=3$ than for $n_{IC}=2$ is true for specified input data. The question is: this conclusion will remain true when the input data will be different.

In this chapter we are doing thermodynamic sensitivity analyses, modifying one by one the irreversibility factors ($\Delta T_{RHE\ relatively}$, $\eta_{is\ K}=\eta_{is\ Tb}$, and $\Delta p_{relatively}$) in order to determine their individual influences, on real cycles computed data, especially on η_{th}, by enlarging the range of input data:

- For ΔT_{RHE}, we choose a scale in geometric progression; the peak value is the double of the reference ($\Delta T_{RHE\ max} \cong 0.125\sqrt{T_{hsa} \cdot T_d}$), and the inferior one, ($\Delta T_{RHE\ min} \cong 0.032\sqrt{T_{hsa} \cdot T_d}$), equal to the half of the reference, with a decrement $\sqrt[10]{10}$.
- For $\eta_{is\ K}=\eta_{is\ Tb}$ we considered a linear variation from 0.88 to 0.94, with a step equal with 0.01;
- For Δp_{rel}, we choose a geometric progression scale with the decrement $\sqrt[20]{10}$, from the maximal $\Delta p_{rel\ max} \cong 4.5$ %, up to the minimal $\Delta p_{rel\ min} \cong 2.2$ % The minimal ratio is the half of the maximal; the reference is the geometric mean.

The main computed data are characterizing:

- Turbo-machineries requirements ($\varepsilon_{K\ r\ gl}$, w_{Tb}, w_K).
- RHE design ($q_{RHE}/q_{RHE\ reference}$, $S_{RHE}/S_{RHE\ ref.}$).
- The cycle's thermal efficiency ($\eta_{th}/\eta_{th\ reference}$).

The obtained results show that, in the given combinations of irreversibility factors, the cycle's thermal efficiencies stays lower for $n_{IC}=3$ than for $n_{IC}=2$. We are ongoing the study for $n_{IC}=1$ and $n_{IC}=2$. With the obtained results for these situations we built fig 6. to 18. The data on Oy axis are given as relative quotas from the references (see the right column of table 1). The abscissa's scale is ranged as the irreversibility going down from left to right.

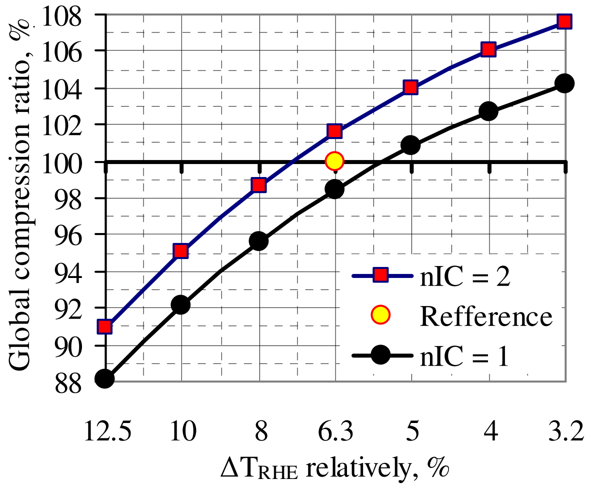

Fig.6 Global compression relative ratio, $\varepsilon_{K\ r\ gl}/\varepsilon_{K\ r\ gl\ reference}$, vs. $\Delta T_{RHE\ relatively}$

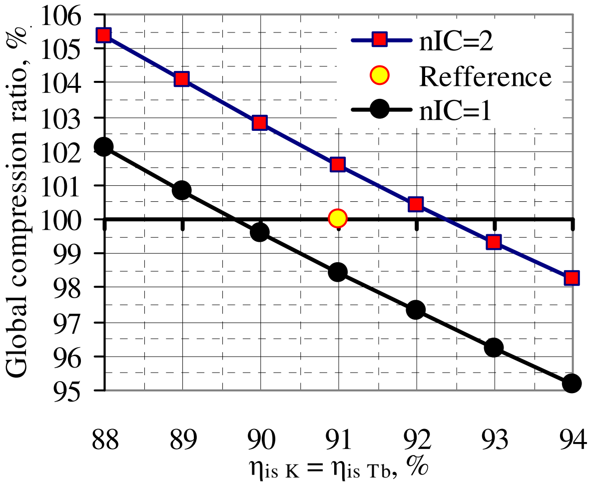

Fig.7 Global compression relative ratio,
$\varepsilon_{K\ r\ gl}/\varepsilon_{K\ r\ gl\ reference}$, vs. $\eta_{is\ K} = \eta_{is\ Tb}$

The global compression's necessary ratio, $\varepsilon_{K\ r\ gl}$, is higher in the n_{IC}=2 design than in n_{IC}=1 scheme (see Fig.6 to 8). In both designs it:

- ✯ increases with ΔT_{RHE} diminish,
- ✯ decreases with $\eta_{is\ K}$=$\eta_{is\ Tb}$ growth,
- ✯ diminishes with $\Delta p_{relatively}$ decrease.

The bigger weight is give by $\Delta p_{relatively}$ followed by ΔT_{RHE}, and the smaller by $\eta_{is\ K}$=$\eta_{is\ Tb}$.

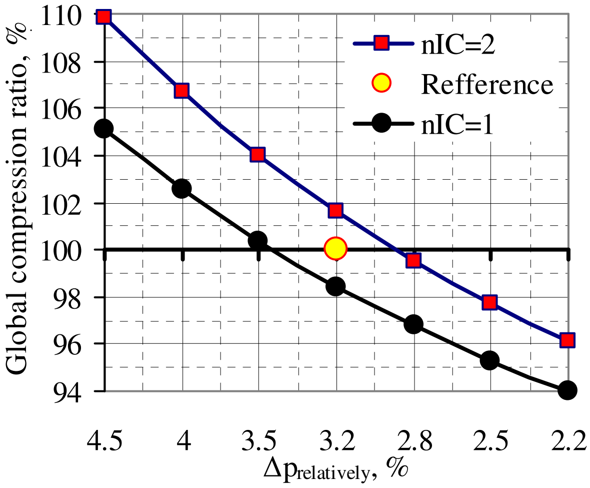

Fig.8 Global compression relative ratio,
$\varepsilon_{K\ r\ gl}/\varepsilon_{K\ r\ gl\ reference}$, vs. $\Delta p_{relatively}$

Fig.9 shows that ***the turbine's generated mechanical work, w_{Tb},*** and ***the compressors work, w_K,*** are strongly influenced by ΔT_{RHE}. Both increase with ΔT_{RHE} diminish, but stay almost the same for n_{IC}=1 and n_{IC}=2 schemes. We mention that w_{Tb} isn't influenced by the others irreversibility factors.

In contrast, w_K, is varying with all the irreversibility factors (see Fig. 9 to 11).

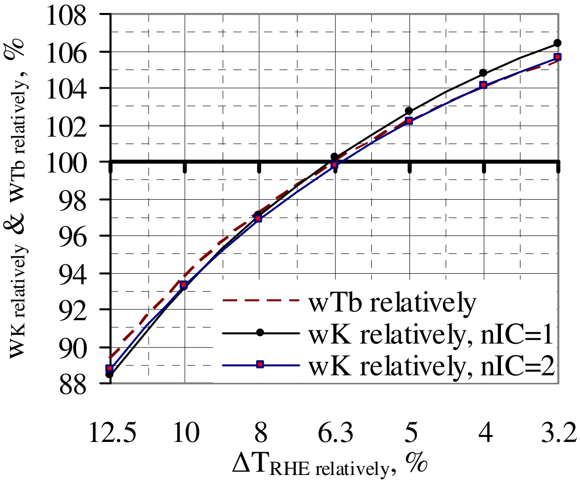

Fig.9 $w_{Tb\ relatively}$ & $w_{K\ relatively}$ vs. $\Delta T_{RHE\ relatively}$

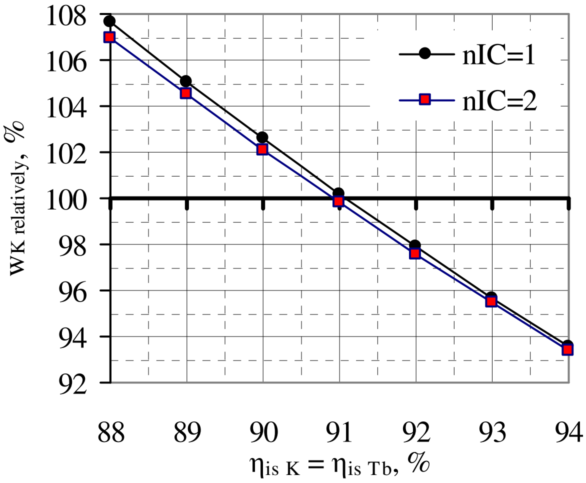

Fig.10 $w_{K\ relatively}$ vs. $\eta_{is\ K} = \eta_{is\ Tb}$

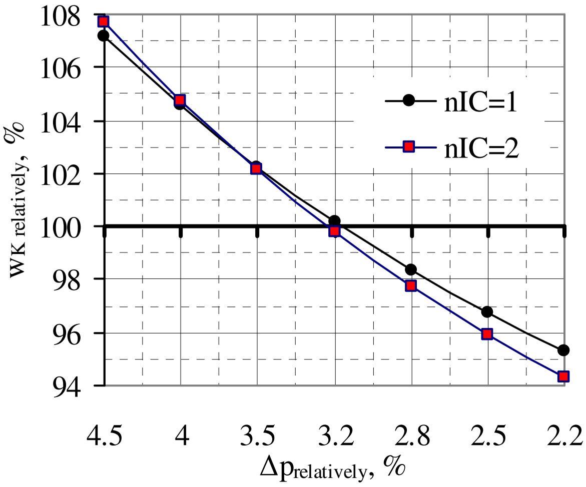

Fig.11 $w_{K\ relatively}$ vs. $\Delta p_{relatively}$

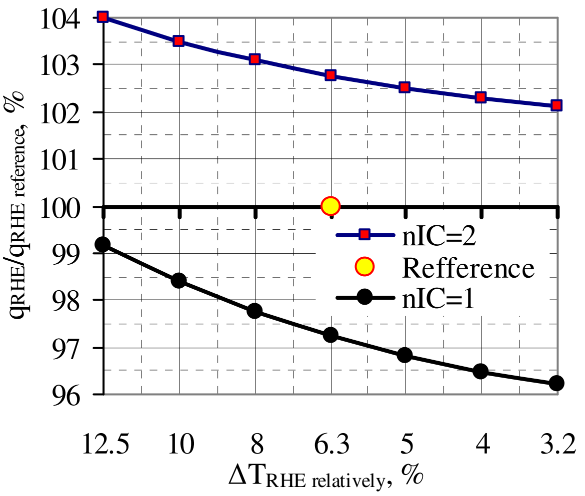

Fig.12 $q_{RHE}/q_{RHE\ reference}$ vs. $\Delta T_{RHE\ relatively}$

It increases, quickly than w_{Tb}, with ΔT_{RHE} growth, and decreases when: **a)** $\eta_{is\ K}=\eta_{is\ Tb}$, goes up, respectively **b)** $\Delta p_{relatively}$ goes down. For $\Delta p_{relatively}$>3.6 %, w_K become higher in the n_{IC}=2 than in n_{IC}=1 scheme. It modifies the quota of compressor's work, related to the turbine one.

In both analyzed designs, for a wide range of input data, the regenerate heat is higher than primary heat (see fig.12 to 14).

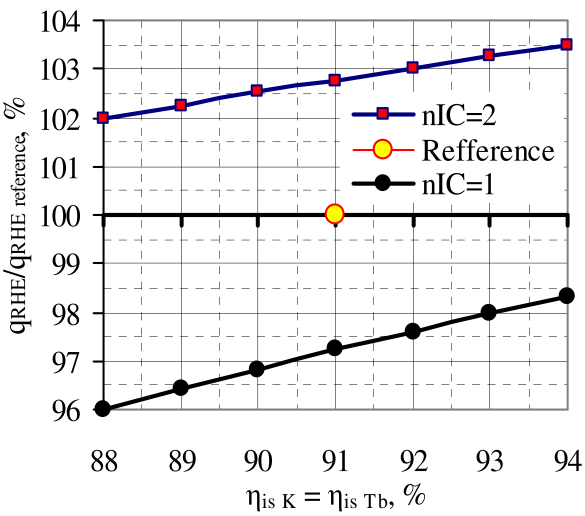

Fig.13 $q_{RHE}/q_{RHE\ reference}$ vs. $\eta_{is\ K} = \eta_{is\ Tb}$

The quota of regenerated heat:

- decreases with ΔT_{RHE} diminish,
- goes up when $\eta_{is\ K}=\eta_{is\ Tb}$ raise,
- increases when $\Delta p_{relatively}$ goes down.

For the entire irreversibilities factor's variation, the relatively deviations are small, less than ±4 % from the reference values.

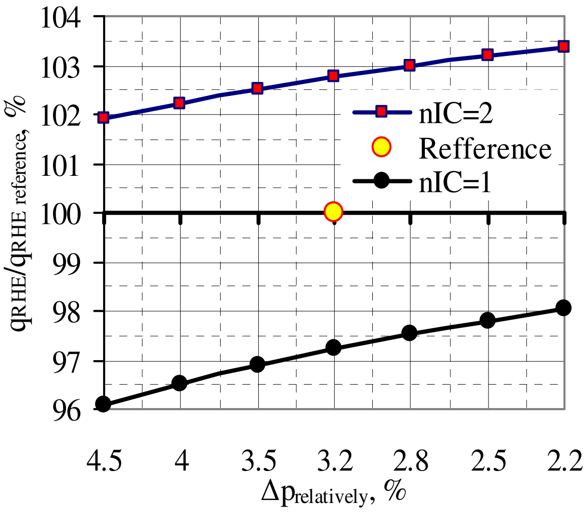

Fig.14 $q_{RHE}/q_{RHE\ reference}$ vs. $\Delta p_{relatively}$

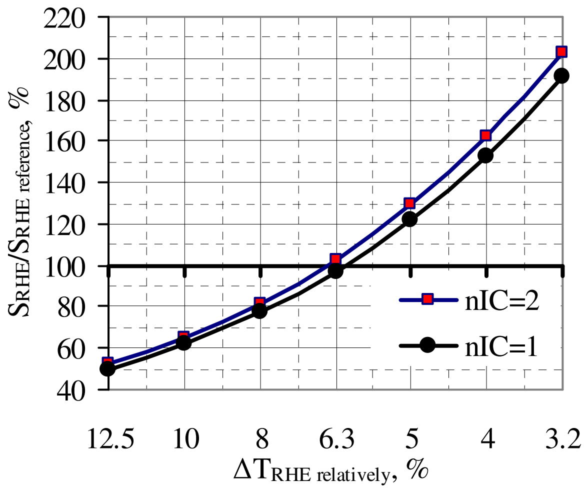

Fig.15 $S_{RHE}/S_{RHE\ reference}$ vs. $\Delta T_{RHE\ relatively}$

The main difference for RHE design is given by ΔT_{RHE}, witch influence ***the active heat exchange surface*** (fig.15). It shows that reducing $\Delta T_{RHE\ relatively}$ at the half of the reference, requires rising the heat exchange surface at 190÷200 % from the reference. Doubling $\Delta T_{RHE\ relatively}$ reduces the surface at 50÷52 % from the same reference value. It inflicts important changes in RHE investment's cost.

The key effects regard ***the thermal cycle's efficiencies***. Because the primary heat is the same, the thermal efficiency is depending only on the net mechanical work. Generally, η_{th} is increasing when irreversibilities are going down. The influences are analogous, but the increasing rates could be different for n_{IC}=1 than for n_{IC}=2. Consequently, some of irreversibility's factors might change the design's classification.

The variation from 88 % to 94 % of $\eta_{is\ K}=\eta_{is\ Tb}$, doesn't change the order: η_{th} stays superior in the n_{IC}=2 design (see Fig.16).

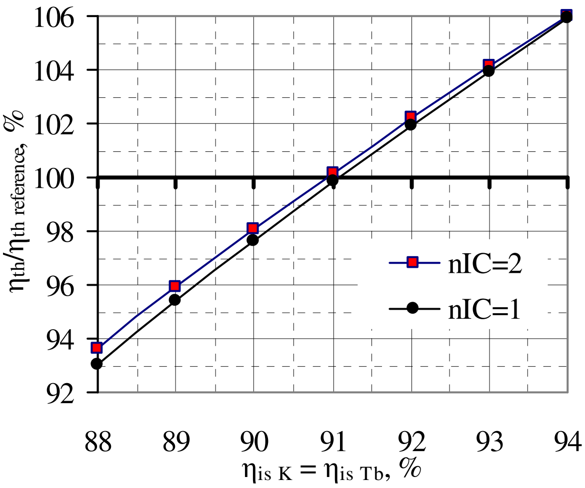

Fig.16 $\eta_{th}/\eta_{th\ reference}$ vs. $\eta_{is\ K} = \eta_{is\ Tb}$

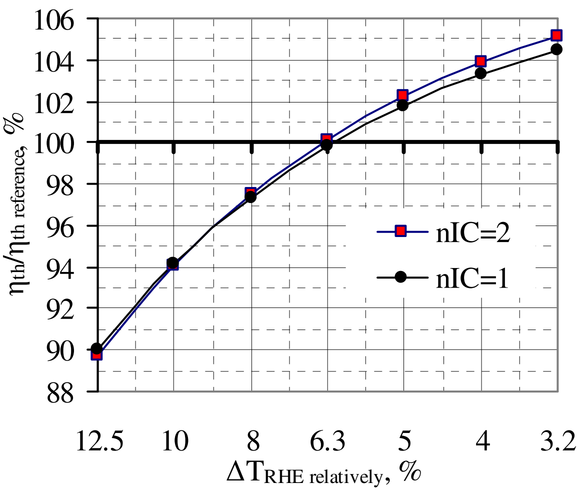

Fig.17 $\eta_{th}/\eta_{th\ reference}$ vs. $\Delta T_{RHE\ relatively}$

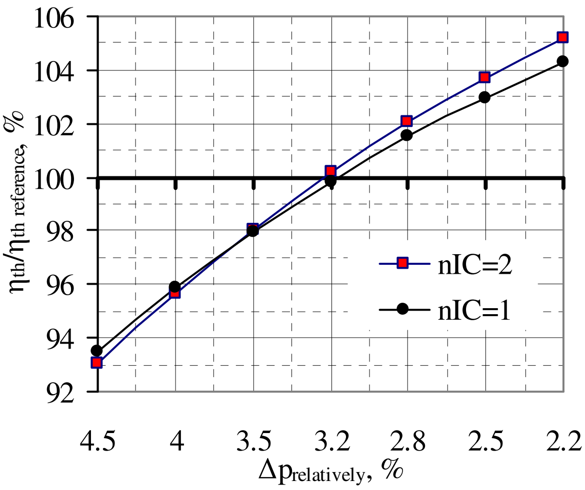

Fig.18 $\eta_{th}/\eta_{th\ reference}$ vs. $\Delta p_{relatively}$

If $\Delta T_{RHE\ relatively}$ and $\Delta p_{relatively}$ are involving higher irreversibilities ($\Delta T_{RHE\ relatively}$>0.1* $\sqrt{T_{hsa} \cdot T_d}$, respectively $\Delta p_{relatively}$>3.5 %), η_{th} become higher in the simplest design, with n_{IC}=1 (see Fig.17, and 18).

5 The Effects of Simultaneously Variation of Irreversibility Factors

In the sensitivity analysis the irreversibility factors where modified individually. In practice it is possible having, at the same time, deviations of 2 or all 3 factors. In this chapter we consider only the situation when all the factors are coincident adjust in the same way: simultaneously reducing all the irreversibilities.

Table 2 shows the combinations between the previous discrete factors, taken in to consideration for building a 7 steps "improvement scale", by simultaneously reducing all the irreversibilities.

Table 2. Numerical values characterizing the "improvement's steps"

Irreversibility axis	maximal → average → minimal						
Irreversibility steps	**1**	**2**	**3**	**4**	**5**	**6**	**7**
$\Delta T_{RHE\ relatively}$, %	12,5	10	8	6,3	5	4	3,2
$\eta_{is\ K} = \eta_{is\ Tb}$, %	88	89	90	91	92	93	94
$\Delta p_{relatively}$, %	4,5	4	3,5	3,2	2,8	2,5	2,2

With these input data we computed the real cycles characteristic output data. Using the results we build fig 19 to 22.

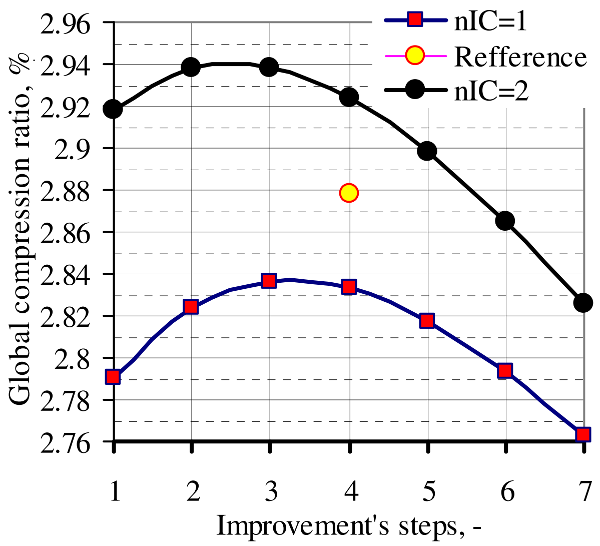

Fig.19 Global compression ratio vs. improvement's steps

The global compression's ratios, $\varepsilon_{K\,r\,gl}$, higher in the n_{IC}=2 design than in n_{IC}=1 scheme (see Fig.19), reaches peak values:

- among the improvement's steps #2&3, for n_{IC}=2;
- at the improvement's step #3, for n_{IC}=1.

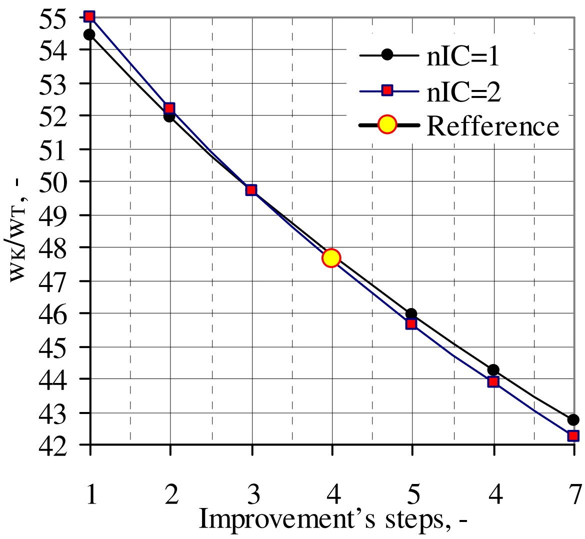

Fig.20 w_k/w_T vs. improvement's steps

Fig.20 shows that the quota of compressors consumed work, divided by the turbines generated work, w_K/w_{Tb}, is weakly influenced by n_{IC}. Starting with improvement's step #3, the ratio w_K/w_{Tb} for n_{IC}=2 is lower than for n_{IC}=1. In both designs it increases with irreversibilities diminish.

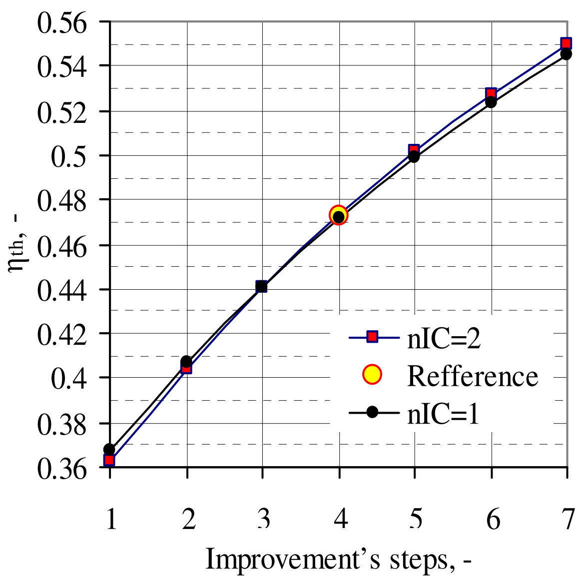

Fig.21 η_{th} vs. improvement's steps

The thermal cycle's efficiency, η_{th}, is strongly influenced by irreversibility factors. It increases when irreversibilities are going down (see fig 21 and fig. 22). The maximal efficiency goes up to 55% (in absolute values), respectively, 116 % from the amount established reference. The minimal one lessens at 36 % (in absolute values), respectively, 76 % from the reference.

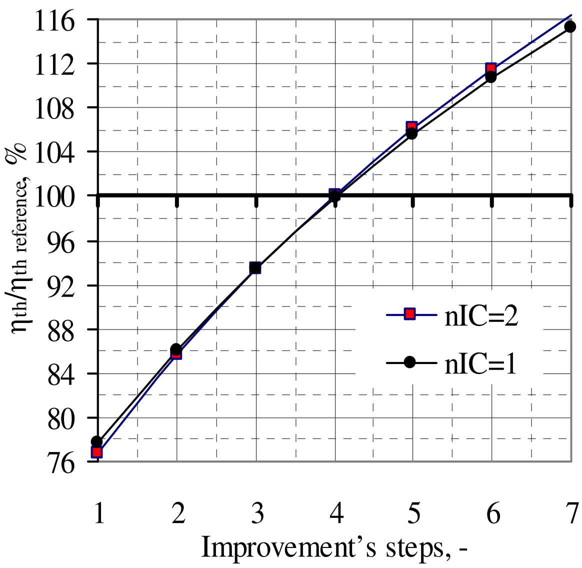

Fig.22 $\eta_{th}/\eta_{th\ reference}$ vs. improvement's steps

The values of η_{th} for n_{IC}=1 and n_{IC}=2 are comparable, but after the improvement's step #3, η_{th} (n_{IC}=2) becomes higher than η_{th} (n_{IC}=1).

6 The Influence of HTGR's Output / Input Temperatures on the Real Cycles Performances

In this chapter we are relaxing the restrictions imposed by the NR, taking into consideration the option that the NR's outlet temperature "T_a"could be dissimilar from the previous fixed value. We considered for T_a a linear variation from 1150 K to 1250 K with a step equal with 50 K. The NR's inlet temperature, T_z, respectively the NR's temperatures difference "$\Delta T_{NR}=T_a-T_z$" should be correlated with the global compression's ratios, $\varepsilon_{K\,r\,gl}$, accordingly to the amount described mathematical relations.

For $\varepsilon_{K\,r\,gl}$ we choose a scale, from $\varepsilon_{K\,r\,gl\,min}$=2 to $\varepsilon_{K\,r\,gl\,max}$=4, in geometric progression. The maximal value is the double of the minimal one, and the growth ratio is $\sqrt[12]{2}$. For the previous reference irreversibilities (improvement's step #4) we where computing the values of T_z, respectively of ΔT_{NR}, depending on $\varepsilon_{K\,r\,gl}$ and T_a (see fig. 23). It shows that ΔT_{NR}, the same in both design, is increasing with

$\varepsilon_{K\,r\,gl}$ and T_a growth.

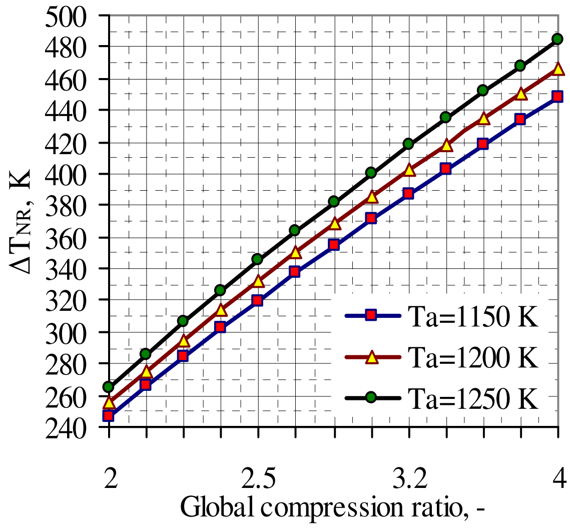

Fig.23 ΔT_{NR} vs. global compression ratio

We stated the NR's relatively temperatures difference, $\Delta T_{NR\ relatively}$, given by:

$$\Delta T_{NR\ relatively} = (T_a - T_z)/\sqrt{T_a \cdot T_z} \qquad (22)$$

, where $\sqrt{T_a \cdot T_z}$ is the geometric average of input / output NR's temperatures. If we know T_a and $\Delta T_{NR\ relatively}$, it is possible to compute ΔT_{NR} in absolute value as:

$$\Delta T_{NR} = T_a \cdot \{1 - \frac{4}{[\sqrt{(\Delta T_{NR\ rel}^2 + 4)} + \Delta T_{NR\ rel}]^2}\} \qquad (22')$$

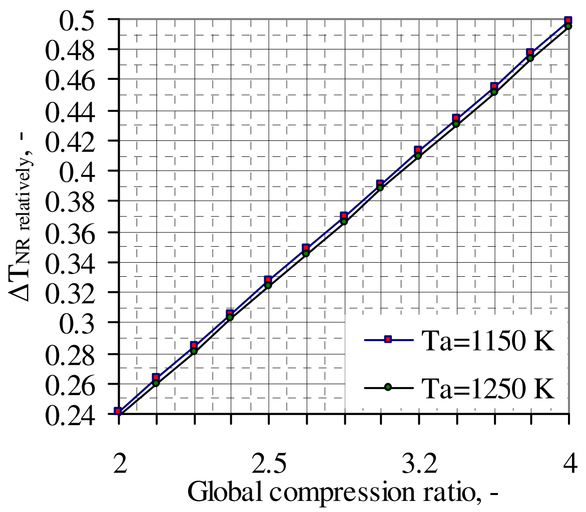

Fig.24 $\Delta T_{NR\ relatively}$ vs. global compression ratio

Fig. 24 shows that $\Delta T_{NR\ relatively}$ is depending mainly on $\varepsilon_{K\,r\,gl}$. Starting from all the 39 chosen and calculated values we established the correlation's equation:

$$\Delta T_{NR\ rel} = 0.36988322 \cdot \ln(\varepsilon_{K\ r\ gl}) - 0.0161489 \qquad (23)$$

The correlation coefficient between data is R^2=0.999662013826965. The average deviation is very small: ± 0.00148914242653972.

The inverse of (23) equation is:

$$\varepsilon_{K\ r\ gl} = e^{[(\Delta T_{NR\ relatively} + 0.0161489)/0.36988322]} \qquad (23')$$

In the next analyses we will utilize the $\Delta T_{NR\ relatively}$ adimensional parameter.

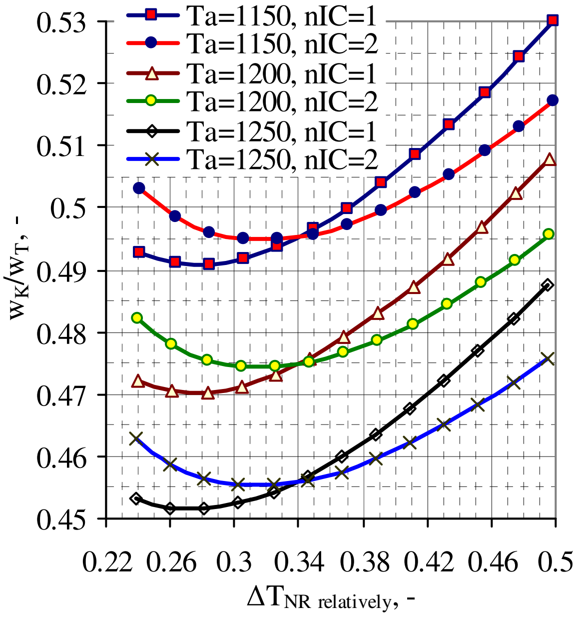

Fig.25 w_K/w_T vs. $\Delta T_{NR\ relatively}$

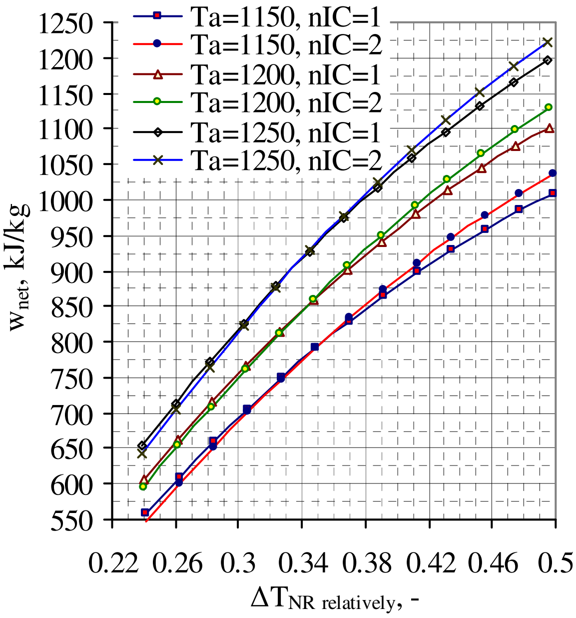

Fig.26 w_{net} vs. $\Delta T_{NR\ relatively}$

Fig. 25 shows the followings:

✯ The quota of compressor's work, divided by the turbine's one, w_K/w_{Tb}, reaches minimal values in the analyzed range of $\Delta T_{NR\ rel}$, along these lines:

- for n_{IC}=1, when $\Delta T_{NR\ rel}$≅0.275, matching to $\varepsilon_{K\ r\ gl}$≅2.2;
- for n_{IC}=2, when $\Delta T_{NR\ rel}$≅0.325, related to $\varepsilon_{K\ r\ gl}$≅2.5.

✯ For $\Delta T_{NR\ rel}$<0.345, corresponding to $\varepsilon_{K\ r\ gl}$≅2.65, w_K/w_{Tb} is lower for n_{IC}=1 than for n_{IC}=2. For $\Delta T_{NR\ rel}$>0.345 w_K/w_{Tb} become higher for n_{IC}=1 than for n_{IC}=2.

✯ The NR's output temperature T_a increasing reduces the ratio w_K/w_{Tb}.

In both design the net work w_{Tb}-w_K is continuously increasing with $\Delta T_{NR\ rel}$ and T_a rising (see fig. 26). For the same $\Delta T_{NR\ rel}$>0.345, corresponding to $\varepsilon_{K\ r\ gl}$≅2.65, w_{Tb}-w_K become higher for n_{IC}=2 scheme.

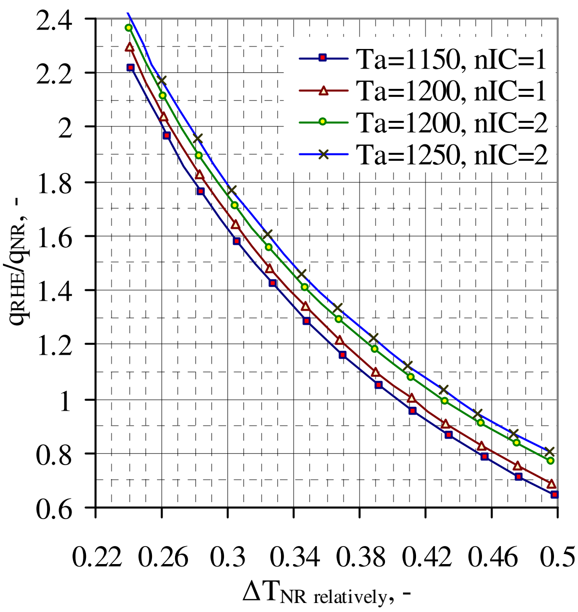

Fig.27 q_{RHE}/q_{NR} vs. $\Delta T_{NR\ relatively}$

The quota of regenerated heat (see fig. 27):

✯ has a variation on a wide domain, decreasing with $\Delta T_{NR\ relatively}$ increases,

✯ for the same T_a is lower in the n_{IC}=1 design than in n_{ic}=2 scheme,

✯ for the same n_{IC} is increasing with T_a grow.

The effects of $\Delta T_{NR\ rel}$ variation on ***the thermal cycle's efficiencies*** are put into evidence in fig. 28:

✯ For $\Delta T_{NR\ rel}$≅0.345, equivalent to $\varepsilon_{K\ r\ gl}$≅2.65, η_{th} are the same for n_{IC}=1 and n_{IC}=2. For $\Delta T_{NR\ rel}$>0.345 η_{th} is higher in the n_{IC}=2 design.

✯ η_{th} reaches peak values in the analyzed range of $\Delta T_{NR\ rel}$, in this manner:

- for n_{IC}=1, when $\Delta T_{NR\ rel}$∈[0.28÷0.285], matching to $\varepsilon_{K\ r\ gl}$∈[2.23÷2.28];
- for n_{IC}=2, when $\Delta T_{NR\ rel}$∈[0.3875÷0.3925], related to $\varepsilon_{K\ r\ gl}$∈[2.98÷3.02].

✯ The maximal efficiencies for n_{IC}=2 design are superior to n_{IC}=1 scheme.

✯ Increasing the NR's outlet temperature T_a leads to η_{th} augmentation.

✯ The values of $\varepsilon_{K\ r\ gl}$ witch allows maximizing η_{th} of FC&IC cycles are much lower than in simple cycle [10].

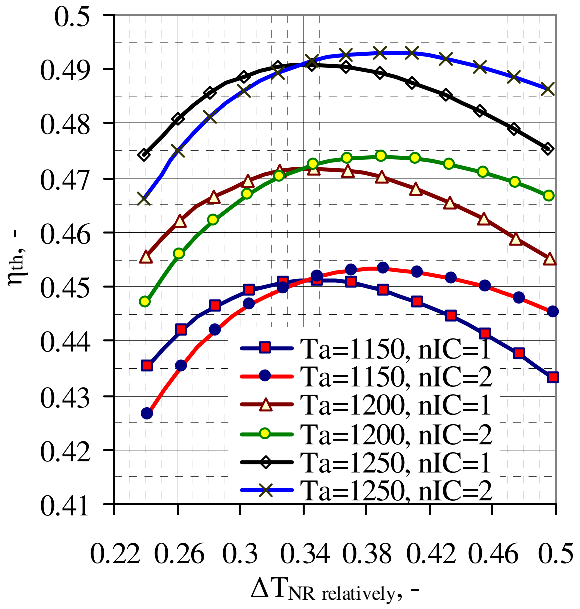

Fig.28 η_{th} vs. $\Delta T_{NR\ relatively}$

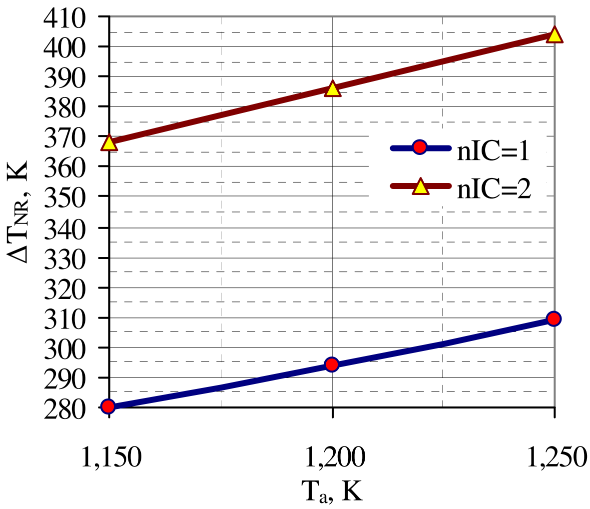

Fig.29 ΔT_{NR} for η_{th} maximizing, vs. T_a

In order to determine the optimal NR's design we computed the absolute values of ΔT_{NR} for maximizing η_{th}. With the obtained values we erected fig. 29. It shows the continuous growth of $\Delta T_{NR}(\eta_{th\ max})$ with T_a increase. For n_{IC}=2 design

$\Delta T_{NR}(\eta_{th\ max})$ is higher with approximately 90 K than for n_{IC}=1 scheme.

7 Conclusions

The first paper's section (up to chapter # 4) refers to comparatively analyzing the influence of irreversibilities causes ($\Delta T_{RHE\ relatively}$, $\eta_{is\ K}=\eta_{is\ Tb}$, and $\Delta p_{relatively}$) on real Brayton cycles (with RHE, FC&IC, for n_{IC}=1 and n_{IC}=2) main indicators. The sensitivity analysis shows that:

- η_{th} is increasing when any of irreversibilities is decreasing. For low irreversibilities it is possible to attain η_{th}>50 %.
- The irreversibilities reasons have comparatively effects on η_{th} (from minus 7÷10 % up to plus 4÷6 % relative to $\eta_{th\ reference}$).
- $\Delta T_{RHE\ relatively}$ influence too the RHE surface, inflicting changes in investment's cost.
- The efficiencies $\eta_{is\ K}=\eta_{is\ Tb}$ have effects on η_{th}, without shifting the performances order; η_{th} is higher in the more complex design (n_{IC}=2).
- When the irreversibilities are bigger than the chosen references (in this case for $\Delta T_{RHE\ relatively}>0.1^*\sqrt{T_{hsa}\cdot T_d}$, or $\Delta p_{relatively}$>3.5 %), the simplest design, with n_{IC}=1, offers in the same time: ***a)*** a lower investment's cost, and ***b)*** a higher thermal efficiencies than n_{IC}=1 design.

In the 5th chapter we considered a simultaneously variation of irreversibility factors, by concomitantly reducing in 7 steps all the irreversibilities. The results show the followings:

- ✯ The global compression's ratios, $\varepsilon_{K\ r\ gl}$, is higher in the n_{IC}=2 design than in n_{IC}=1 scheme and reaches peak values among the improvement's steps #2&3, for n_{IC}=2, respectively at the improvement's step #3, for n_{IC}=1.
- ✯ The ratio $\boldsymbol{w_K/w_{Tb}}$, is weakly influenced by n_{IC}. In both designs it increases with irreversibilities reducing. Starting with improvement's step #3 it becomes lower for n_{IC}=2 than for n_{IC}=1.
- ✯ The thermal efficiencies are strongly influenced by irreversibility factors. They increase when irreversibilities are going down up to 55% (in absolute values), respectively, 116 % from the amount established reference. The minimal values lessen at 36 % (in absolute values), respectively, 76 % from the reference. The values of η_{th} for n_{IC}=1 and n_{IC}=2 are comparable, but after the improvement's step #3, $\eta_{th}(n_{IC}=2)$ becomes higher than $\eta_{th}(n_{IC}=1)$.

In chapter # 6 we where relaxing the restrictions imposed by the NR, taking into consideration different output / input temperatures (T_a/T_z) from the previous fixed ones. It shows their influence on the real cycle's performances:

- ✯ For the same n_{IC}, the NR's output temperature T_a increasing reduces the ratio $\boldsymbol{w_K/w_{Tb}}$.
- ✯ $\boldsymbol{w_K/w_{Tb}}$, reaches minimal values in the analyzed range of $\Delta T_{NR\ relatively}=(T_a-T_z)/\sqrt{T_a\cdot T_z}$
- ✯ The quota of regenerated heat has a large variation, decreasing with $\Delta T_{NR\ relatively}$ increases. For the same T_a it is lower in the n_{IC}=1 design than in n_{ic}=2 scheme, and for the same n_{IC} is increasing with T_a grow.
- ✯ The effects of $\Delta T_{NR\ rel}$ variation on the thermal cycle's efficiencies are the followings:
  - For $\Delta T_{NR\ rel}\cong0.345$ ($\varepsilon_{K\ r\ gl}\cong2.65$), $\boldsymbol{\eta_{th}}$ is the same in both designs. If $\Delta T_{NR\ rel}$>0.345, $\boldsymbol{\eta_{th}}$ is higher in the n_{IC}=2 scheme.
  - $\boldsymbol{\eta_{th}}$ could be optimized in the analyzed range of $\Delta T_{NR\ rel}$. For n_{IC}=1 it happens when $\Delta T_{NR\ rel}\cong0.283$ ($\varepsilon_{K\ r\ gl}\cong2.25$), and for n_{IC}=2, when $\Delta T_{NR\ rel}\cong0.39$ $\varepsilon_{K\ r\ gl}\cong3$.
  - The maximal efficiencies for n_{IC}=2 design are superior to n_{IC}=1 scheme.
  - Increasing the NR's outlet temperature T_a leads to $\boldsymbol{\eta_{th}}$ augmentation.
- ✯ The absolute values of $\Delta T_{NR}=T_a-T_z$ for maximizing $\boldsymbol{\eta_{th}}$ are continuously growing with T_a increase. For n_{IC}=2, $\Delta T_{NR}(\eta_{th\ max})\in(368÷404)$ K, being higher with approximately 90 K than $\Delta T_{NR}(\eta_{th\ max})\in(280÷309)$ K, for n_{IC}=1 scheme.

The general directions for optimizing the performances of HTGR's Helium Brayton cycles with FC&IC are: **A)** reducing the irreversibilities and choosing the correct design, correlated with them; **B)** increasing the NR's outlet temperature and choosing the optimal $\Delta T_{NR}=T_a-T_z$, according to T_a and the scheme's design. The ΔT_{NR} choice involves the value of compression ratio.

References:

[1] LaBar, M.P., The Gas Turbine – Modular Helium Reactor: A Promising Option for Near Term Deployment, *General Atomics*, April 2002. GA-A23952 (http://www.doe.gov).
[2] MacDonald, P.E., Very High Temperature Gas-cooled Reactor (VHTR), *Workshop for Universities - Advanced Reactors, Fuel Cycle, and Energy Products, U.S. Department of Energy, Rockville,* 2005, pp.384-450.
[3] Boyce, M.P., *The Gas Turbine Engineering Handbook*, third edition, Gulf Professional Publishing, Oxford and other., 2006.
[4] Alexe, Fl., Cenuşă, V., Analyzing the Brayton cycle for high temperature helium cooled

nuclear reactors, *Energie – Environnement - Economie & Thermodynamique (COFRET)*, Nantes - France, 11-13 juin 2008, L 13.

[5] Feidt M., *Thermodynamique et Optimisation Energétique des Systèmes et Procédés*, 2ème édition Tec&Doc, 1996.

[6] Moran M., Shapiro, *Fundamentals of Engineering Thermodynamics*, 5th edition, John Wiley & Sons, New York, 2004.

[7] D.I. Petrilean, I. Dosa, Calculus of Indicated Power by Mathematical Modeling Method of Compression Process and Study of Exergetic Efficiency of the Helical Screw Compressor with Oil Injection, *WSEAS TRANSACTIONS on FLUID MECHANICS*, Vol.3, No.4, 2008, pp. 339-348.

[8] R. Molaei, M. Ebrahimi, S. Sadeghian and B. Fahimnia, Genetic Algorithm-Based Optimization of Fuel Consumption in Network Compressor Stations, *WSEAS TRANSACTIONS on APPLIED and THEORETICAL MECHANICS*, Vol.2, No.12 2007, pp. 251-259.

[9] L.A. Khan, A. El-Ghalban, Heat Exchanger Exergetic Lifecycle Cost Optimization using Evolutionary Algorithms, WSEAS TRANSACTIONS on HEAT and MASS TRANSFER, Vol.3, No.1 2008, pp. 125-136.

[10] V. Cenusa, and F. Alexe, Comparative Analysis on Performances of Micro Gas Turbines Burning Biogas vs. Natural Gas, *WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT*, Vol.3, No.4, 2007, pp. 72-80.