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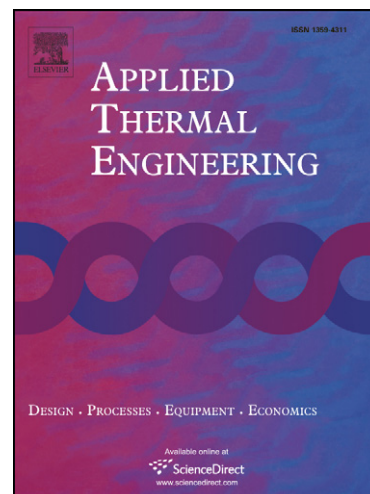
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POWER CYCLE ASSESSMENT of NUCLEAR HIGH TEMPERATURE GAS-COOLED REACTORS

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ABSTRACT

This century power engineering is facing up to one of the greatest challenges ever posed to humankind: the achievement of a sustainable energy system. In order to respond to this challenge, Nuclear Technology is designing a new generation of power plants termed Generation IV, among them High Temperature Gas-cooled Reactors stand out for their potential capability to achieve an excellent thermal performance. This paper investigates the thermal and economic performance of several direct Brayton cycle configurations that could be used in future HTGRs, with special attention to the effects of inter-cooling and reheating. Among the hypotheses and assumptions taken, the adoption of the PBMR reactor parameters and settings as a reference is particularly important. All inter-cooled layouts have shown thermal efficiencies near or even higher than 50%, which means a substantial improvement with respect to non-intercooled baselines with no economic penalties. Reheating has been shown not to affect remarkably the thermal or economic plant performance under base-load operation, but it provides the plant with such a flexibility that allows its operation under the “load-follow” regime without heavily taxing the thermal or economic performance. Anyway, use of a multiple axes configuration instead of a single one seems to worsen plant economics and not to entail any thermal benefit.

KEY WORDS: power cycles, high temperature gas-cooled reactors, Generation IV nuclear systems

1. INTRODUCTION

This century power engineering is facing up to one of the greatest challenges ever posed to humankind: the achievement of a sustainable energy system. Most scientists and engineers agree that such a system should consider all the present and future energy sources with a proven sustainable performance. As a matter of fact, according to the International Energy Agency has recently stated that in the near- and mid-term (2010-2050) the decarbonisation of the power sector would include, amongst others, 55 fossil-fuelled power plants with CCS (CO₂ Capture and Storage), 32 nuclear plants, 17500 large wind turbines, and 215 million square metres of solar panels [1]. Nuclear Technology is getting ready to respond to such a challenge in even a longer term (beyond 2040) with innovative, more economically competitive, non-proliferant and even safer power plant designs. As a whole, these new designs have been termed Generation IV [2].

Nonetheless, at present nuclear energy production is almost exclusively focused on electricity generation, which accounts for only 16% of the energy consumed worldwide (being nearly 80% of the remaining energy obtained by burning fossil fuels [3]). Therefore, nuclear energy contribution to overcome issues like depletion and supply shortages of fossil fuels and global warming would be vigorously reinforced if a wider energy market was addressed. Industrial heat consumption is a good candidate to accomplish such a diversity of energy products. However, most of the industrial process heat applications require much higher temperatures than the operating temperatures of present Light Water Reactors (LWR). Besides, the amount of energy required is never more than a few hundred MWs, while the present systems become competitive only for a thermal production of a few thousand MWs.

One of the Generation IV systems, the so called High Temperature Gas-cooled Reactors (HTGRs), can produce heat at high or very high temperature (HTR and VHTR, respectively) using a few hundred MW reactors. In other words, HTGRs (sometimes referred to as HTRs also) have the potential to address a wide range of industrial applications both related to process heat, electricity and combined heat and power generation (cogeneration). The high temperature of the heat source, allows considering applications like the CO₂-free hydrogen production or oil refining, which require high quality energy, and

others like desalination or district heating, which demand much lower temperature heat. It is noteworthy that HTGRs residual heat sources have exergy levels well over the characteristic ones of LWRs.

The interest in HTGRs, particularly those designs cooled by helium, has been reinforced even further by their capability of reaching thermal efficiencies in between 40 and 50% (substantially higher than those accomplished by present nuclear technology, ~30-36%). This achievement, now feasible thanks to advances in turbo-machinery and high temperature materials, entails major benefits for the energy system, such as less fuel consumption, drastically reduced waste production and, additionally, a lower cost of nuclear kWh.

This paper has a two-fold objective: to illustrate the thermal performance of several power cycle configurations based on parameters and settings of upcoming HTGRs and to assess the economic performance of the explored layouts. Direct closed Brayton layouts have been explored and specific attention has been given to the effects of single and multiple turbine-compressor arrangements (1-axis vs. 3-axes) and to the influence of inter-cooling and reheating cycle performance.

2. THEORETICAL APPROACH

This section compiles the main equations others than the generic expression of cycle thermal efficiency,

$$\eta = \frac{W_{\text{net}}}{Q_H} \quad (1)$$

used in the thermal and economical modeling of the power cycles simulated below.

2.1. Thermal and Mechanical equations

Equations describing in a generic way the energy input/output in the cycle components (i.e., compressors, intercoolers and turbines) are based on the energy balance and thermal efficiency concepts derived from the First and Second Law efficiencies:

$$\dot{W}_c(i, i+1) = \dot{m}_T \cdot (1-\beta) \cdot \frac{c_p}{\eta_c} \cdot T(i) \cdot \left[\left(\frac{P(i+1)}{P(i)} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (2)$$

$$\dot{Q}_{ic}(i, i+1) = \dot{m}_T \cdot (1-\beta) \cdot c_p \cdot [T(i) - T(i+1)] \quad (3)$$

$$\dot{W}_T(i, i+1) = \dot{m}_T \cdot (1-\beta) \cdot c_p \cdot \eta_T \cdot T(i) \cdot \left[1 - \left(\frac{P(i+1)}{P(i)} \right)^{\frac{\gamma-1}{\gamma}} \right] \quad (4)$$

where β is 0 for cycles without reheating; “i” characterizes the gas state before undergoing the component effect. Equations (2) and (4) assume isentropic compressor efficiency, which is the traditional approach in adiabatic analysis of turbomachinery [4]. Equation (3) comes from the energy balance set in the heat exchanger.

The pressure drop through the reactor vessel has been modelled by the Ergun equation, which was specifically derived for pebble beds [5]:

$$\frac{\Delta P}{\rho \cdot L} = \left(\frac{v_o^2}{d_p} \right) \left(\frac{1-\alpha}{\alpha^3} \right) \cdot \left[170 \cdot \frac{v}{v_o \cdot d_p} \cdot (1-\alpha) + 1.75 \right] \quad (5)$$

This expression provides a good description of the flow resistance in the entire Reynolds range

($Re = \frac{v_o \cdot d_p}{\nu}$), whenever fuel pebbles is approximately spherical and their individual diameter meets the conditions that

$$d_p < \frac{1}{20} \cdot d_r$$

In addition, heat exchanger effectiveness of the recuperator (RHX) has been estimated assuming a plate-fin configuration [6],

$$\varepsilon = 1 - 2.718282^{(-2 \cdot NTU)} \cdot [I_o \cdot (2 \cdot NTU) + I_1 \cdot (2 \cdot NTU)] \quad (6)$$

whereas those of the pre- and inter-coolers have been calculated as shell-and-tube heat exchangers [6]:

$$\varepsilon = \frac{n \cdot \left(\frac{-\varepsilon_1}{1-\varepsilon_1} \right)}{n \cdot \left(\frac{-\varepsilon_1}{1-\varepsilon_1} \right) - 1} \quad (7)$$

Where n is the number of shell passes and ε_1 is the effectiveness in the case of a single shell pass,

$$\varepsilon_1 = \frac{2}{2 + \sqrt{2} \cdot \frac{1 + e^{-\sqrt{2} \cdot NTU}}{1 - e^{-\sqrt{2} \cdot NTU}}} \quad (8)$$

As noted, the recuperator has been chosen to be a plate-and-fin heat exchanger since it plays a key role in the thermal efficiency of the system. Additionally, A less relevant role is played by pre- and inter-coolers that can be considered “low-power heat exchangers”, as compared to the recuperator. They have been considered shell-and-tube heat exchangers to reduce the capital investment.

2.2. Economic analysis

The economic analysis has been focused on three major features of a project: investment, levelized cost and feasibility. Investment estimate has been based on the El-Sayed methodology [7], whereas assessments of levelized cost and feasibility (i.e., net present value and internal rate of return) have followed Bejan’s approach [4].

El-Sayed methodology relies on component cost functions (Z_i) that depend on variables such as pressure ratio, mass flow rate, pressure drop, etc. right on the cycle design point. Initially, it was developed to deal with combined cycles, so that gas turbine cycle components are modelled with high accuracy. The overall fixed capital investment results from adding the individual functions with respect to 1999 costs and from updating the result according to the time correction proposed in the Chemical Engineering Plant Cost Index (CEPCI):

$$FCI = \frac{CEPCI_{2006}}{CEPCI_{1999}} \sum_i Z_i \quad (9)$$

The cost function of the nuclear reactor is missing in El-Sayed [7]. A value of the reactor cost has been derived by applying the El-Sayed methodology to already published fixed capital investment data concerning the 168 MWe PBMR power plant [8].

3. APPLICATIONS

By using the methodology presented above some specific features of potential power cycles of HTGR reactors have been explored and are illustrated next.

3.1. HTGRs background

Research and development of high temperature gas cooled reactors have been fostered in the last ten years all over the world. Nonetheless, the development of the HTGRs has been an evolutionary process spanning over more than four decades [9]. A few reactors were already commissioned in the 1960s, like Dragon, Peach Bottom and AVR. Then, other more evolved concepts, like Fort Vs. Vrain and THTR-300, were built-up and operated. Despite these plants could not demonstrate the commercial capabilities of the HTGR, they were certainly valuable in demonstrating attributes of a huge importance, as the performance of the TRISO coated fuel particles. All the research and development associated to these and other HTGR reactors was carried out essentially by Germany, U.S., Russia and United Kingdom.. At present, in addition to test reactors, like the HTTR in Japan [10] or the HTR-10 in China [11], several prototype reactors are to be constructed in forthcoming years.

Early High Temperature Gas cooled Reactors (HTGRs) were based on the Rankine steam cycle. However, current plant designs favour the Brayton cycle, either direct or indirect. Some designers prefer indirect Brayton cycles because they add an additional barrier against potential radioactive contamination

of the turbo-machinery and allow for some flexibility in the choice of the secondary coolant gas and in the coupling of process heat units. This is the case of the ANTARES project [12] where the nuclear heat source is supplied through an Intermediate Heat Exchanger (IHX) to a combined cycle, where the topping Brayton cycle employs a mixture of nitrogen and helium as the working fluid.

Most of present HTGR projects, however, are of a direct type. Designers point out several advantages with respect to indirect cycles, like the 2-3% higher efficiencies or the avoidance of the problems associated to the use of an IHX (i.e., cost increase, licensing difficulties, potential for leaks, etc.). Some of these HTGRs, like the Chinese HTR-10GT [13] (10 MW_{th}) and the American-Russian GT-MHR [14] (600 MW_{th}), include in their configurations compression inter-cooling and thermal energy recovery from turbine exhaust gas as ways to enhance thermal efficiencies. Others, like the Japanese GTHT300 [15] (600 MW_{th}), ruled out the use of inter-coolers, despite the 2% efficiency gain, because of the added complexity to turbo-machinery.

This power cycle diversity is even greater. Sometimes different power cycle configurations can be coupled to the same nuclear system depending on applications. Thus, the MHR [16] (Modular Helium Reactor), as other HTGRs, is a good candidate to produce hydrogen and its cycle configuration will be different depending on the technology to be used, either thermo-chemical cycles or high temperature electrolysis.

The PBMR [17] (Pebble Bed Modular Reactor) is by itself an example of the BOP variety. The 400 MW_{th} demonstration power plant to be built by ESKOM in South Africa will rely on a direct inter-cooled and recuperative Brayton cycle to produce electricity. From this basis two different applications are foreseen: an Advanced Electricity Plant (AEP-PBMR) and a Process Heat Plant (PHP-PBMR). The former will couple a PBMR reactor to a combined cycle consisting of a topping Brayton cycle and a bottoming Rankine cycle, whereas several configurations have been shown to be feasible for the latter to produce different proportions of high temperature steam and electricity (as typically required by petrochemical plants).

Recently, some studies have been carried out to explore thermal performance of this type of plants. Fröling et al. [18] analysed several options of power cycles for a 200 MWth reactor: steam turbine, gas turbine and, even, combined cycles. They identified the most influencing variables of each configuration and obtained efficiencies as high as 47.5% for the direct combined cycle layout. Other researchers focused their thermal analysis on specific plant designs, as Sen et al. [19] who studied the PBMR BOP and Oh et al. [20] who dealt with a 250 MWth HTGR (High Temperature Gas Reactor) unit. The former [19] conducted a systematic analysis based on a simplified PBMR layout consisting of a two compression stages, a single stage turbine and a recuperator. They sought for optimum thermal efficiencies by parametrically change high pressure and temperature from 7 to 10 MPa and from 900 to 950°C, respectively. Their analysis pointed out that the case of 10 MPa and 900°C was the one of highest thermal efficiency (40%). Oh et al. [20] found out thermal efficiencies rather higher (from 45 to nearly 52%, depending on core outlet temperature -850-1000 °C) for an indirect plant layout where the intermediate heat exchanger was shown to play a key role in the whole system.

3.2. Reference layouts

In view of the interest of BOP and the alternatives proposed as power cycles for next HTGRs, their technical and economic performance is of utmost interest. This paper is focused on direct Brayton cycle layouts and it explores the effect on the thermo-economic performance of the nearest projects in time: the number of turbomachinery axes and the presence in the system of inter-coolers (in between compressors) and reheaters. A triple axis configuration has been proposed by ESKOM for the PBMR plant, whereas a single axis configuration is intended for the MHR reactor. On the other side, even though the thermal benefit of intercooling is well known, projects like the GTHTR300 disregard its inclusion, so that an analysis of its effect deserves further attention. Finally, reheating has the potential to enhance performance and operation flexibility of Brayton cycles. A quantitative assessment of its impact in actual power layouts could give interesting insights on its potential.

The notation used is the one proposed by Hawthorne [21]. For comparison purposes all the main parameters and settings in the above layouts have been those of the PBMR reactor since it is presently the best characterized in the open literature.

Figures 1 (a) and (b) display the two versions analyzed of direct Brayton cycles: 1-axis inter-cooled layout (CICHTXP) and 3-axis inter-cooled and reheated layout (CICHRTXP), respectively. As observed, the reheating strategy is based on using just a fraction of the gas exiting the reactor ($1-\beta$) to power compressors, the remaining β fraction being used to heat up the ($1-\beta$) stream before expanding in the power turbine. Therefore, in this configuration just a fraction ($1-\beta$) of the gas mass flow rate gets eventually expanded in the power turbine. In spite of this, reheating has been shown to be able to provide an effective way to improve plant performance under load follow operation mode [22].

3.3. Main hypotheses

Based on the open and recent literature on the matter, the main technological hypotheses assumed were the following:

- Helium (He), given its monoatomic nature as a noble gas, has been assumed to behave as an ideal gas with constant specific heat ($c_p=5.193$ kJ/kg-K; $\gamma=1.67$) [4].
- Inlet temperature to compressors has been set to 30°C [20], which is achievable with the cooling medium used (i.e., water).
- Outlet reactor temperature and pressure have been set to 1173 K and 90 bar, respectively, as stated in references [17, 23].
- Cooling medium is water from a cooling tower which operates with air at 25°C (dry bulb temperature), 50% relative humidity and 101.3 kPa. Wet bulb temperature approach is 5°C. These conditions are usually adopted to set the power plants design in Spain.
- Isentropic efficiencies of compressors and turbines have been set to 90% [20] and 93% [24], respectively. The recuperator has been scaled to reach an effectiveness of 95% in the baseline case [24]. Pre- and inter-coolers have been modelled as heat exchangers with a 95% effectiveness in the

baseline case, which is an achievable value with the proper number of shell passes (as noted in Eq. (6) shown above).

- Pressure drop along lines has been considered negligible. However, 0.4 bar [20] has been set in the pre- and inter-cooler. Likewise, pressure loss in the recuperator has been given specific values [7,23]

$$\Delta P_{X,HP} = 0.5 \text{ bar}$$

$$\Delta P_{X,LP} = 0.8 \text{ bar}$$

- PBMR reactor vessel dimensions [17] have been adopted to estimate pressure drop through the “heat source component”. The resulting pressure loss resulting from Eq. (5) below, has been shown to be consistent with the values reported in refs. [17,20].

The major economic assumptions taken are:

- Economic life assumed to be 60 years [23]. Levelized costs for operation and maintenance (16 \$/MWh, with a nominal cost growth of 2,5%/yr), for fuel (8 \$/MWh, with a nominal cost growth of 3,5%/yr) and discount rate of 10% have been scaled from Kuhr et al. [25] to consider the effect of extending plant economic life from 35 to 60 years.
- An inflation of 3% has been considered (usual value at Spain [26]).
- Electricity price set as in Spain production market during 2006 (65.81 €/MWh) [27].

3.4. Results and discussion

Non-reheating layouts

The inter-cooling effect has been investigated through the configurations of the three existing VHTR options [28]: GT-HTR (a 1-axis cycle), GT-MHR (a 1-axis inter-cooled cycle) and PBMR (a 3-axis inter-cooled cycle). The three layouts have been compared in terms of thermodynamic and economic variables.

A preliminary study was carried out to determine the highest thermal efficiency of each layout as a function of mass flow rate (\dot{m}) and pressure ratio (r), assuming a thermal power of 500 MWth. Figure 2 shows that the presence of an inter-cooler entails two major changes in the operation conditions

corresponding to the maximum efficiency: a higher pressure ratio (2.9 versus 2.54) due to the fluid pressure loss along across the component, and a mass flow rate reduction of around 10% (260 kg/s versus 295 kg/s) to produce the same power output.

Regardless the changes in the nominal operation conditions, Table I shows that inter-cooling enhances substantially thermal efficiency (near 51% in the 1-axis configuration and more than 51% in the 3-axis baseline). Gas density increase due to the temperature decrease resulting from inter-cooling, reduces the power required by compressors and, as a consequence, thermal efficiency grows roughly 4 points over the non-intercooled option. Contrarily to the noticeable effect on the system thermal performance, plant economics is hardly affected by inter-cooling (LEC and FCI vary less than 3% each) whenever the number of axes is not changed. Use of multiple axes, however, penalize plant economics, although it may provide some flexibility to turbo-machinery operation.

Reheating layouts

From the results presented above, this section shows the effect of reheating in the inter-cooled 1-axis and 3-axes configurations. Figures 3 and 4 summarize the results found.

The maximum net power produced corresponds to $\beta=0$ (no reheating); in other words, the enthalpy gain of the $(1-\beta)$ gas fraction in the reheater does not compensate the inventory loss caused by the extraction. No major differences are noted regarding the plant performance between the two axis arrangements. Thus, in both cases the optimum thermal efficiency is attained when around 30% of the gas exiting the reactor is used as a secondary heat source; the maximum value of efficiency reaching almost 50%. Even more important than such a high thermal efficiency is the fact that such a good behaviour holds in a broad range of extracted gas fractions: variations of β between 0.0 and 0.5 would never result in thermal efficiencies lower than 48.5%. Namely, a power decrease down to 50% of the nominal value would not yield in substantial efficiency losses that would tax the kWh production cost.

Contrarily to what has been observed in terms of thermal performance, the 3-axis configuration raises the LEC substantially (around 25%) with respect to that of the 1-axis. Nonetheless, none of the layouts

entailed changes in LEC higher than 0.2 €/MWh (<1% of the net LEC value) as power is reduced to 50% of the maximum output.

Therefore, reheating does not result in improvements of thermal and/or economical performance of the plant (i.e., higher thermal efficiency and power output or lower LEC and capital investment), but it provides the plant with an outstanding operation flexibility that makes it thermally and economically efficient under load-follow conditions (the net power can be fitted to demand with minor losses of thermal efficiency and maintaining electricity production cost).

Table II compiles thermal and economical variables that summarize the overall performance of both configurations at their nominal point ($\beta=0.2$). The figures in the table underline the above observations regarding similarity in thermal behavior and economical advantages of the 1-axis arrangement over the 3-axes one.

Even though results in Table I and Table II apparently indicate a better economic performance of non-reheating plants (no major differences noted in the thermal performance), under the hypotheses and assumptions of this study, such a comparison is not suitable. Reheating plants allow a load-follow operation mode so that they could participate in the electricity market out of the “base load regime”, where electricity sales are usually more profitable. These considerations have not been accounted for when assessing investment and LEC. Anyway, if the power plant had to work permanently under base load mode, consideration of reheating would be meaningless.

CONCLUSIONS

The thermal and economic assessments of direct closed Brayton cycles for future HTGRs have allowed to explore different power cycle configurations and to investigate the quantitative effects of inter-cooling and reheating. Among the hypotheses and assumptions taken, the adoption of PBMR parameters and settings as a reference has to be highlighted. Some of the main conclusions drawn from the results obtained may be synthesized as follows:

- The good thermal performance (i.e., high thermal efficiencies) of direct closed Brayton cycles, such as defined by foreseen parameters and settings, make HTGR reactors potential candidates to significantly contribute to a sustainable energy system in which reduction in consumption of natural resources and waste generation is highly valued. Even further, the high quality of the thermal energy generated enable nuclear technology access to energy markets other than electricity, like heat process, hydrogen generation and others.
- Inter-cooling has the capability of raising thermal efficiency of power cycles significantly, without taxing the economic performance of the plant.
- Use of a multiple axes configuration does not lead to any major thermal improvement with respect to the 1-axis arrangement and it penalizes plant economics (this being further accentuated if reheating is considered). Nonetheless, the impact on turbo-machinery operation may be improved, but such a regard is out of the scope of this paper.
- Reheating is a powerful strategy to increase plant operation flexibility without drastically losing competitiveness. Nonetheless, the load-follow operation mode is worth being further investigated to test off-design turbo-machinery performance and reliability and to achieve a full economic characterization that accounts for indicators other than LEC, such as NPV, IRR and PP.

Finally, it is interesting to realize that according to the electricity price taken as a reference (65.81 €/MWh in Spain in 2006), any of the baselines explored in this paper would be competitive in the Spanish electricity market.

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ACRONYMS

AEP	Advanced Electricity Plant
BOP	Balance Of Plant
CEPCI	Chemical Engineering Plant Cost Index
CICHTRTXP	Notation used to define the power cycle layout (see the text)
FCI	Fixed Capital Investment
HTGR	High Temperature Gas-cooled Reactor
HTR	High Temperature Reactor
IHX	Intermediate Heat Exchanger
IRR	Internal Rate of Return
LEC	Levelized Electricity Cost
LWR	Light Water Reactor
MHR	Modular Helium Reactor
NPV	Net Present Value
NTU	Number of Thermal Units
PBMR	Pebble Bed Modular Reactor
PHP	Process Heat Plant
RHX	Recovery Heat eXchanger
VHTR	Very High Temperature Reactor

NOMENCLATURE

c_p	Specific heat at constant pressure [kJ/kg-K]
d_p	Pebble diameter in a fluidized bed reactor [m]
d_r	Reactor hydraulic diameter [m]
I_i	Modified Bessel functions of first kind [-]
L	Reactor characteristic length [m]
\dot{m}_r	Through-reactor mass flow rate [kg/s]
n	Number of shell passes in a heat exchanger [-]

P	Pressure [bar]
\dot{Q}_{ic}	Heat rejected in the inter-cooler [kW]
Q_H	Heat supplied to the cycle [kW]
r	Pressure ratio [-]
Re	Reynolds number [-]
T	Temperature [K]
v_o	Fluid velocity [m/s]
\dot{W}_c	Compressor power [kW]
W_{net}	Net power output from the cycle [kW]
\dot{W}_T	Turbine power [kW]
Z_i	Cost function of component “i” [\$ ₁₉₉₉]
α	Reactor void fraction [-]
β	Gas fraction extracted [-]
ΔP	Pressure drop in reactor [bar]
	Pressure drop in high pressure side of recuperator [bar]
$\Delta P_{X,HP}$	
$\Delta P_{X,LP}$	Pressure drop in low pressure side of recuperator [bar]
ε	Heat exchanger effectiveness [-]
γ	Specific heat ratio [-]
η	First Law efficiency [-]
η_i	Isoentropic Efficiency of “i” component [-]
ν	Kinematic viscosity [m ² /s]
ρ	Fluid density [kg/m ³]

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FIGURE CAPTIONS

Fig 1. Closed Brayton reference layouts

Fig 2. Thermal efficiency maps defined by mass flow rate and pressure ratio in non-reheating layouts

Fig. 3. Characteristics variables of the 1-axis CICHTRTXP layout as a function of extracted fraction

Fig. 4. Characteristics variables of the 3-axes CICHTRTXP layout as a function of extracted fraction

Table I. Technical and economical performance of non-reheating direct layouts

	1-axis		3 axes
	CHTXP	CICHTXP	CICHTXP
Thermal Power (MW)	500	500	500
Efficiency (%)	46.9	50.7	51.1
Mass flow rate (kg/s)	295	260	256
Pressure ratio (-)	2.55	2.90	2.93
LEC (€/MWh)	36.0	35.0	40.3
FCI (€/kW)	1241	1202	1622
NPV (M€)	1344	1464	1377
IRR (%)	29.7	30.6	24.5

Table II. Technical and economical performance of reheating layouts ($\beta=0.2$)

	1 axis	3 axes
Thermal Power (MW)	406	407
Efficiency (%)	49.6	49.7
Mass flow rate (kg/s)	267	265
Pressure ratio (-)	2.9	2.93
LEC (€/MWh)	38.2	48.2
FCI (€/kW)	1444	2231
NPV (M€)	1117	974
IRR (%)	26.6	19.7

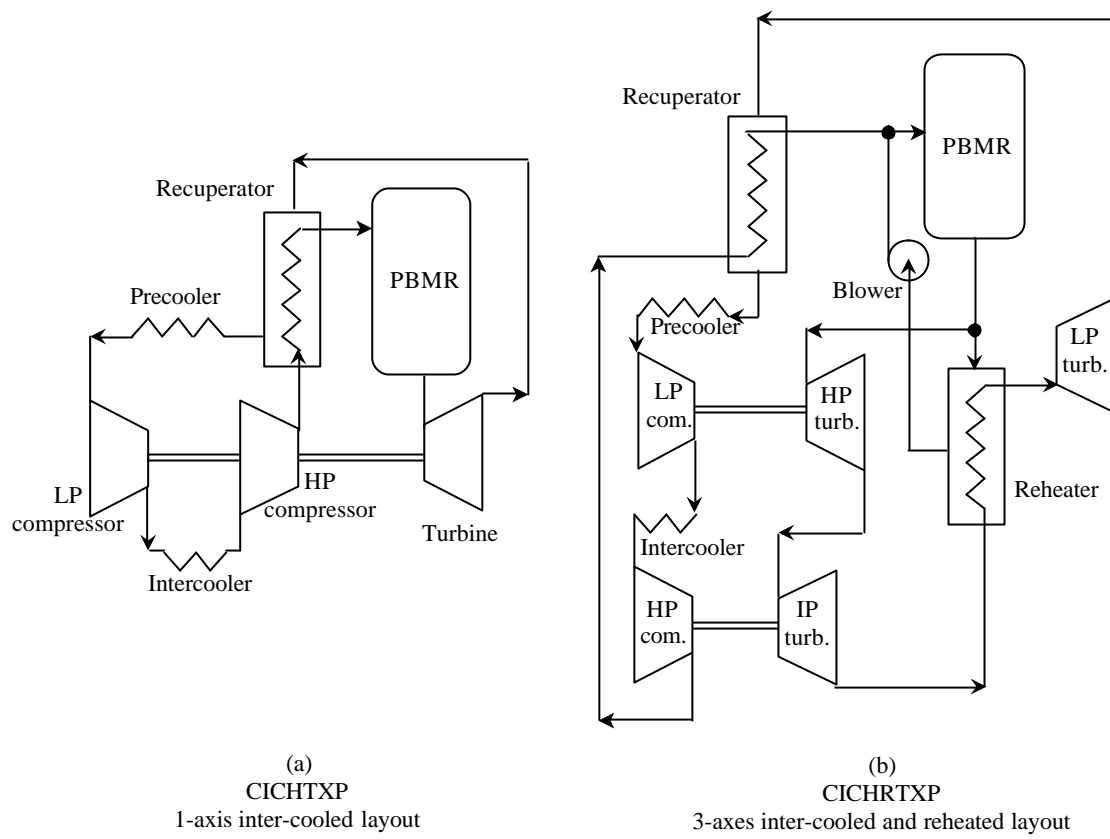


Figure 1

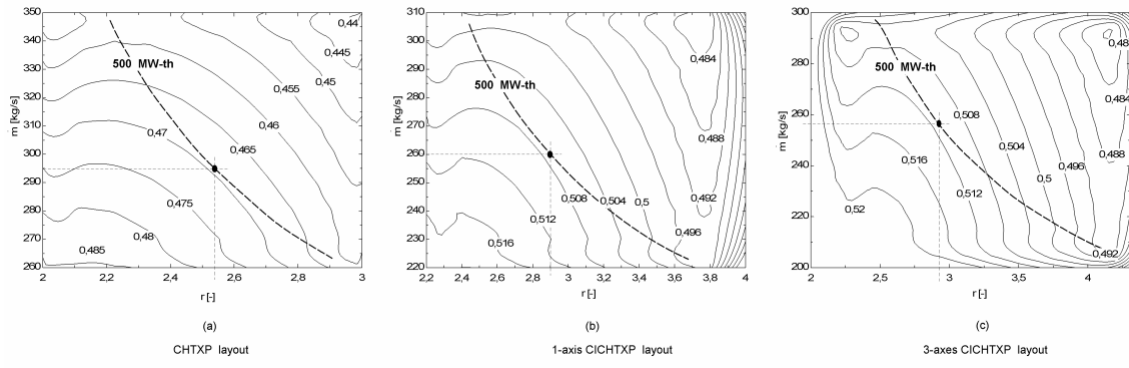


Figure 2

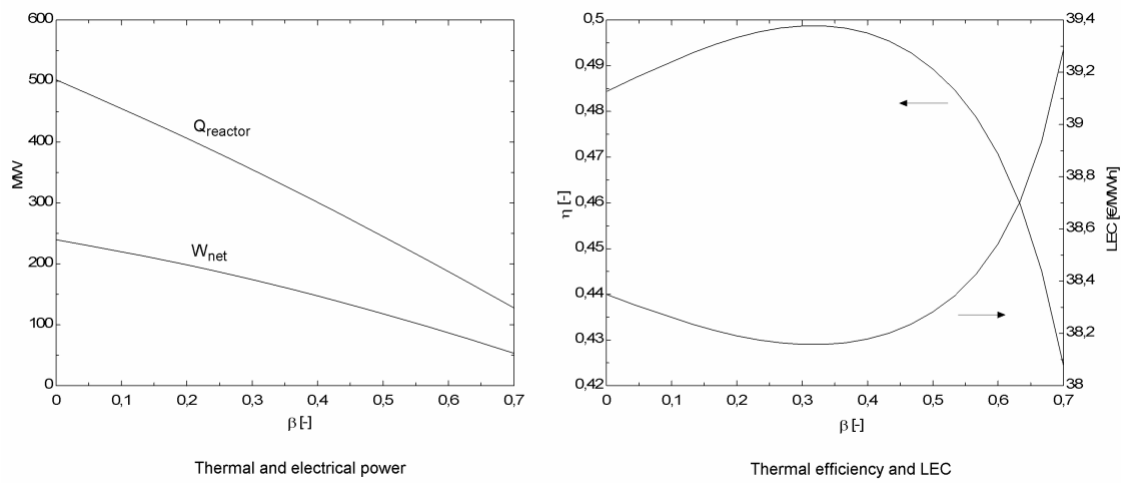


Figure 3

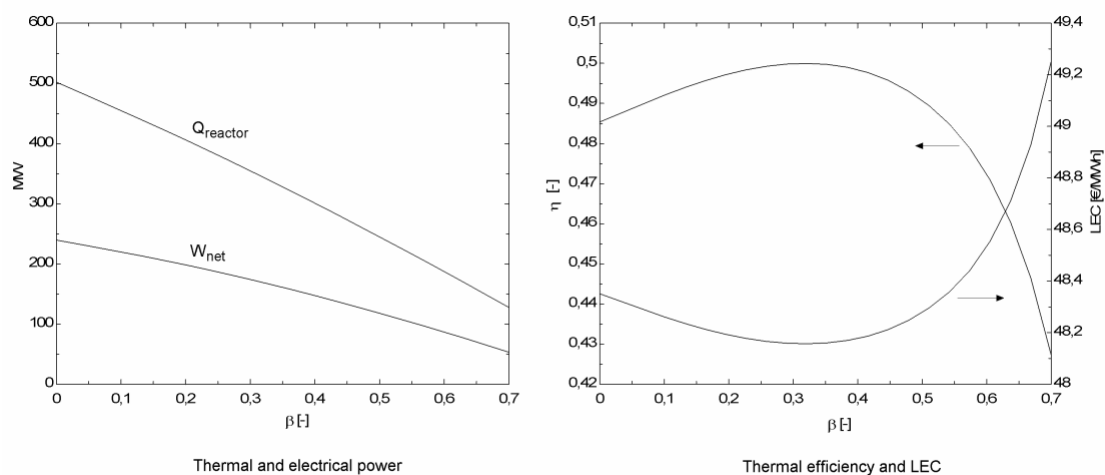


Figure 4