Thermodynamics Cycle of Gas-Cooled Fast Reactor

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This paper deals with the thermo-hydraulic aspect of gas cooled fast 4 generation reactor. The paper is focused on the comparison of direct and indirect strategy of thermodynamics cycle of helium cooled reactor from the thermodynamics and turbomachinary point of view. The analyses respect pressure looses at all major part of the equipment - reactor, heat exchanger, pipe lines, etc. The compressor and gas turbines efficiency are includes in calculation as well.The working fluid in primary circuit is helium. In the secondary circuit a mixture of helium and nitrogen is considered. The Cycle characteristic point and efficiency calculation reflects mixture properties of the real gas. Calculation point out the influence of mixture composition on the basic structural parameters of the turbines, compressor and heat exchangers. Thermodynamics cycle efficiency, specific heat input/output , heat flux and cycle work will be presented as characteristic parameters.

Keywords: Thermodynamic cycle, Generation IV reactor, Gas cooled reactor, Gas turbine.

1. Introduction

There are a lot of advantages on the side of gas-cooled fast reactors [11]. They do not suffer with weaknesses such as sodium cooled fast reactors. The gas is chemically inert and a single phase coolant eliminates boiling. Gas also allows high temperature operation without the corrosion and coolant radiotoxicity problems associated with heavy liquid metal reactors (Pb-Bi and pure Pb). On the other hand, gas coolants have little thermal inertia rapid heat-up of the core following loss from forced cooling. The motivation for this project was to determine the optimal effectivity and specific work of direct (Figure 1) and indirect (Figure 2) cycle strategy of gas cooled reactors and propose an optimal solution for gas cooled fast reactors [1] [2].
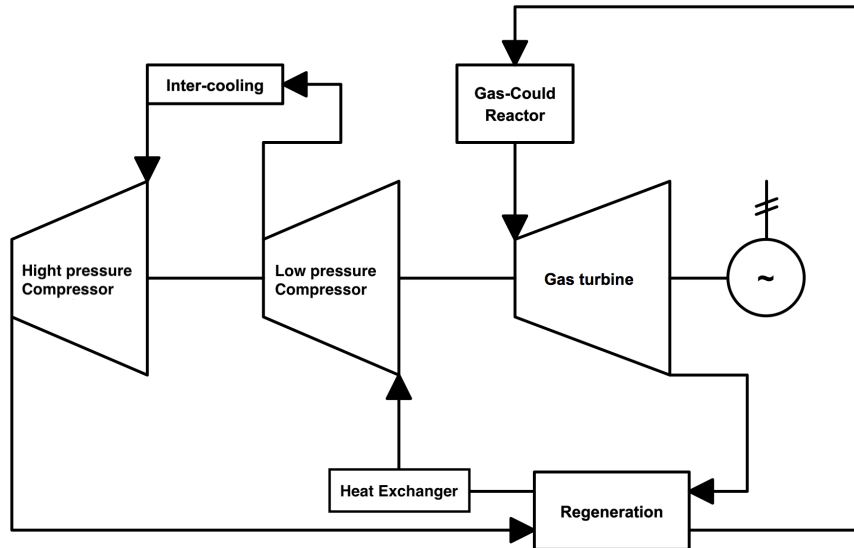
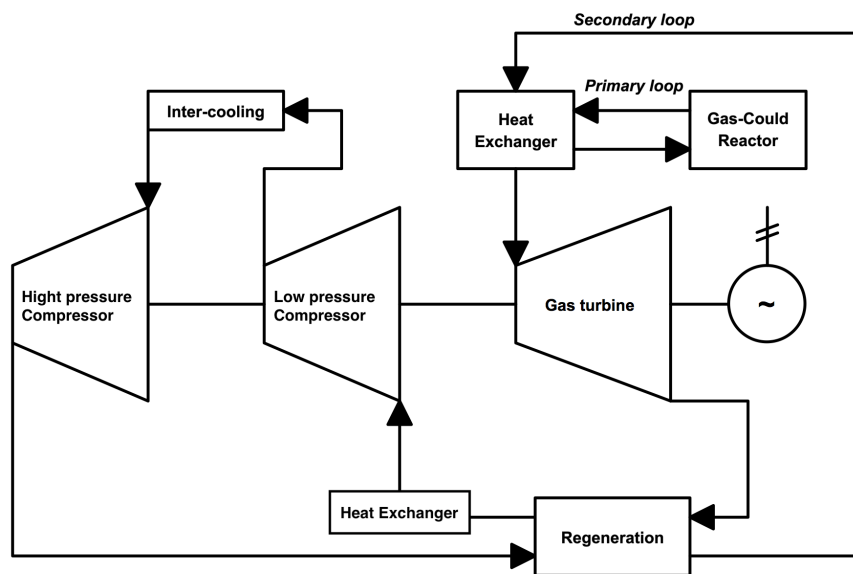**Figure 1** Direct thermodynamics cycle

Figure 2 Indirect thermodynamics cycle

2.   Model description

The computational models of the direct and indirect cycles are described by analytical and empirical equations of thermodynamics, fluid mechanics and turbomachinery [3] [6] [7] . Efficiency and specific work for arbitrary thermodynamics cycle can be determined as a follow function:

$$\eta = f(\lambda, \tau, \eta_t, \eta_c, \Sigma) \tag{1}$$

$$W_{net} = c_p \ \dot{m} \ T_{min} \ g(\lambda, \tau, \eta_t, \eta_c, \Sigma) \tag{2}$$

Our model respect thermophysical properties of ideal gas (used mainly for He), thermodynamics of isentropic, isobaric and polytropic transformations, thermophysical properties of real gas [5] (used mainly for N_2), pressure losses of reactor and heat exchangers, efficiency of turbine and compressor stages, and effectivity of heat exchangers and regenerator.

2.1.   *Non-dimensional parameters*

Thermodynamics characteristics of different cycles can be describe by set of non-dimensional parameters [8] [9]:

- Isotropic Temperature ratio: $\lambda = \frac{T_2^{is}}{T_1}$

- Pressure ratio: $\epsilon = \frac{P_{max}}{P_{min}}$, respectively: $\lambda = \epsilon^{\frac{\kappa-1}{\kappa}}$

- Temperature ratio: $\tau = \frac{T_{max}}{T_{min}}$, (in our case is $T_{min} = T_1$)

- Regenerator efficiency: $\Sigma_1 = \frac{T_2^{''} - T_2}{T_4 - T_2}$

- Heat exchanger efficiency: $\Sigma_2 = \frac{T_6 - T_1^{''}}{T_5 - T_1^{''}}$

- Non dimensional specific cycle work: $w_{net}^* = \frac{W_{net}}{c_p T_{min} \dot{m}}$

- Non dimensional input specific heat: $q_{in}^* = \frac{Q_{in}}{c_p T_{min} \dot{m}}$

- Non dimensional output specific heat input/output: $q_{out}^* = \frac{Q_{out}}{c_p T_{min} \dot{m}}$

2.2.   *Cycle thermodynamics characteristics*

Cycle efficiency as a function of different degree of regeneration, turbine and compressor efficiency and various thermodynamics transformation of Joule cycle (see Figure 3) is described by equations (3), (4), (5), (6) and (7) [8].

Cycle efficiency, ideal case, isentropic compression & expansion without regeneration:

$$\eta^{base} = \frac{\lambda - 1}{\lambda} \tag{3}$$

respectively with regeneration:

$$\eta^{reg} = \frac{\tau - \lambda}{\tau} \tag{4}$$

Cycle efficiency, ideal case, isotermic compression & expansion without regeneration:

$$\eta^{bese} = \frac{(\tau - 1)ln\lambda}{\tau ln\lambda + \tau - 1} \tag{5}$$

respectively with regeneration (equivalent to Carnot efficiency)

$$\eta^{reg} = \frac{\tau - 1}{\tau} \tag{6}$$

Cycle efficiency respecting devices efficiency (isentropic c&e)

$$\eta = \frac{\lambda - 1}{\lambda} \frac{\tau\eta_t - \frac{\lambda}{\eta_c}}{(1 - \Sigma)(\tau - 1 - \frac{\lambda-1}{\eta_c}) + \Sigma\tau\eta_t\frac{\lambda-1}{\lambda}} \tag{7}$$

Equation (7) can be modify by pipelines and reactor pressure losses and C_p correction, if $C_p \neq constant$ etc. Regeneration is valid for:

$$\lambda \in (1, \sqrt{\tau\eta_t\eta_c}) \tag{8}$$

For higher λ is $\Sigma = 0$ (system without regeneration). Optimal temperature ration for max. cycle work is:

$$\lambda|_{w_{net}^{max}} = \sqrt{\tau\eta_t\eta_c} \tag{9}$$

The heat fluxes are apparent on the Figure 3. The waste heat energy of the primary cycle can be used as an input energy for secondary thermodynamics cycle, or as technological heat for additional technology such as hydrogen production [10].

3. Results

3.1. *Number of turbine stages*

Number of turbine stages significantly depends on blade to gas speed ratio $\sigma = u/c_{is}$ (schematically shown on Figure 4), where $c_{is} = \sqrt{2h}$. The typical optimal value of impulse turbine stage is $\sigma \approx 0.5$.

Optimal number of turbine stages can be defined by equation :

$$n_{opt} = f(RPM, C_p, \kappa, R_{opt}, \sigma_{opt}, \epsilon_{turb}) \tag{10}$$

For total turbine efficiency we can use simplified function : $\approx f(\eta_{stage}^n, ...)$ Typical number of stages and efficiency of conventional gas turbines diameter 2.5 m, RPM 3000 and different working gas are shown in Table 1.

Figure 3 Temperature-entropy diagram of Joule combined cycle and waste heat using

Figure 4 Blade to gas speed ratio $\sigma = u/c_{is}$

Table 1 Typical number of turbine stage

Gas used	He	N_2	$10\%He + 90\%N_2$
Num. of stages	16	3	8
Total Turbine Efficiency.	0.7	0.9	0.8

3.2. *Effect of compressor and turbine efficiency*

Figure 5 shows the effect of the compressor and the turbine efficiency on the specific cycle work w_{net} and on the overall efficiency of the entire cycle. By decreasing the turbine and the compressor efficiency the w_{net} and the cycle efficiency curves move to lower values of λ.
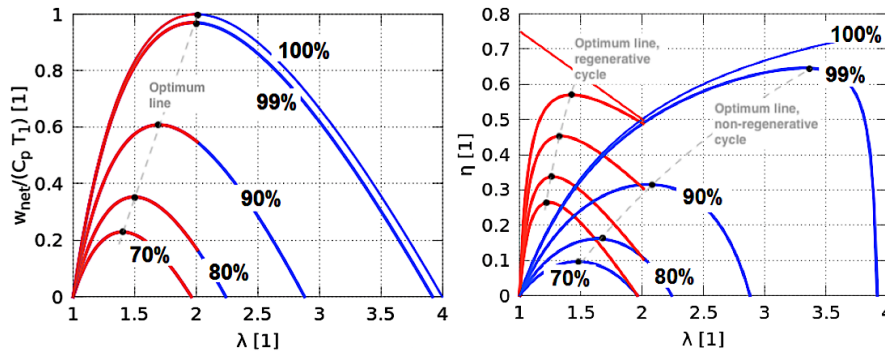
Figure 5 Specific work (left) and thermodynamic cycle efficiency (right) as a function of compressor and turbine efficiency, temperature ratio $\lambda = 4$

3.3. *Combine cycle*

One of the example is the indirect combined cycle with $He - N_2$ (20% - 80%) mixture for the intermediate gas cycle.

The efficiency of the Brighton cycle with regeneration and inter-cooling (secondary loop) is approximately 26% [9] and the efficiency of the Ranking cycle (tertiary loop) is 25% [9] (correspond with results [1]). Total efficiency of the combined power plant is based on equation (11). In our case the result is around ±45%. An additional water loop uses the waste heat from a secondary (Helium) loop. A part of this heat energy is moved to the conventional steam cycle, see Figure 6.

$$\eta_{c-c} = \eta_{HT} + \eta_{LT} - \eta_{HT}\eta_{LT}, \tag{11}$$

where η_{HT} is efficiency of the high temperature primary cycle and η_{HN} is efficiency of the low temperature secondary cycle. Example of thermodynamic parameters of the combine cycle is apparent on the Table 2.

4. Conclusion

The long-term development of gas turbine engines for aircraft and cogeneration has been in favour of the indirect cycle. The concept of a gas turbine for air (used for N_2 or N_2 and He mixture) have higher efficiency numbers in comparison with the helium turbines today. Indirect cycle - decrease the energy flux in the

Table 2 Example of characteristic input/output parameters

Characteristic parameters	values	units
Gas Turbine input/output Temperatures	850 / 510	°C
Gas Turbine input/output Pressures	7.02 / 2.65	MPa
Compressor input/output Temperatures	178 / 362	°C
Compressor input/output Pressures	2.6 / 6,5	MPa
Compressor Pressure Ratio	2.5	-
Steam Turbine input/output Temperature	535 / 32	°C
Steam Turbine input/output Pressures	15 / 0.005	MPa
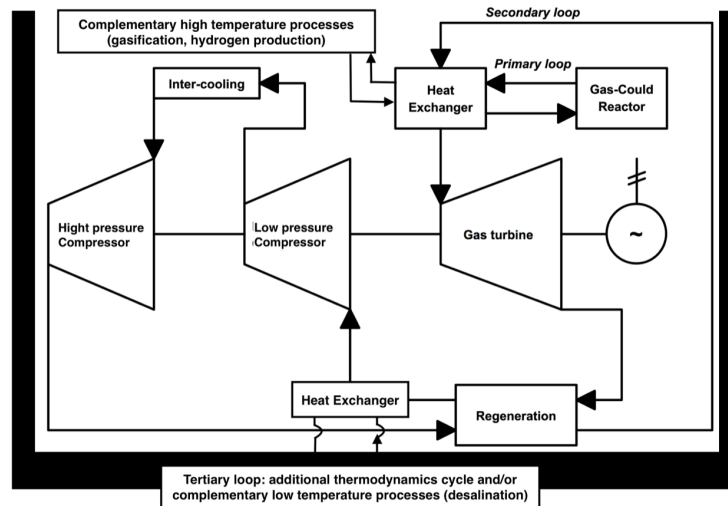
Figure 6 Scheme of indirect combine cycle

second working media approximately 2-3 times (depending on gas mixture). It cause robust construction of heat exchangers, dimensions of turbines, compressors pipelines and other cycle components, but required lower no. of compression and expansion stages. The thermodynamic cycle analysis presented here should help in the design process of the optimal variant according to the actual efficiencies of the components. Development of each component will push the limits forward.

References

[1] **Anzieu, P., Stainsby, R., Mikityuk K.**: Gas-Cooled Fast Reactors: Overview and Perspectives, *AMEC, Paul Scherrer Institut*, **2007**.

[2] **Kevan, D. Weaver**: Interim Status Report on the Design of Gas-Cooled Fast Reactors. *Gen IV nuclear energy systems, INEEL/EXT-05-02662.*

[3] **Horlock, J. H.**: Combined Power Plants: Including Combined Cycle Gas Turbine Plants, *ISBN-13: 978-157524*, **1975**.

[4] **Thomas, Y. C. W., Kevan, D.W.**: Initial Requirements for Gas-Cooled Fast Reactor System Design, Performance, and Safety Analysis, *Gen IV nuclear energy systems, INEEL/EXT-04-02242.*

[5] **Wagner, W.**: Description of the Software FLUIDCAL for the Calculation of Thermo-dynamic and Transport Properties, *RUHR-UNIVERSITAT BOCHUM, Fakultat fur Maschinenbau, www.ruhr-uni-bochum.de/thermo.*

[6] **Dixon, S. L, Hall, C. A.**: Fluid Mechanics and Thermodynamics of Turbomachinery, *ISBN 978-1-85617-793-1*, **2010**.

[7] **Horlock, J. H.**: A Combined Power Plants: Including Combined Cycle Gas Turbine Plants, *ISBN-13: 978-1575241975* **1992**.

[8] **Bidard, R., Bonnin, J.**: Energetique at turbomachines, *ISBN 978-2-212-01583-6*, **1979**.

[9] **Polansky, J., Gaspar, R.**: Optimization of the Thermodynamics Cycles of Generation IV Gas-Cooled Fast Reactors, *Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition*, San Diego, USA, IMECE2013-64565, **2013**.

[10] **IAEA**: IAEA Nuclear Energy Series Technical Reports Hydrogen Production Using Nuclear Energy, STI/PUB/1577 (978-92-0-135110-4), No. NP-T-4.2, **2012**.

[11] **Mitchell, C., Poette, P. K., Coddington, P., Somers, J., Van-Goethem, G.** GCFR: The European Unions Gas Cooled Fast Reactor Project, *Proceedings of ICAPP 06 Reno, NV USA, June 4-8, Paper 6311* , **2006**.