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Thermodynamic Analysis and Optimization of Helium Ericsson Power Cycle: A Novel Model for Pseudo-isothermal Compression and Expansion

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Abstract: *Nuclear energy has been considered as clean and environmentally friendly method of power production. With the emergence of Generation IV reactor, a new horizon was opened in nuclear technology. The invention of new materials and production processes and magnetic bearings, the new ideas for increasing the efficiency of nuclear power plants are being considered more feasible. In this paper the thermodynamic analysis of a Helium pseudo-isothermal expansion and compression power cycle which can be utilized to couple with a Very High-temperature Gas Reactor (VHTR) was performed. A novel thermodynamic modelling of estimating the isothermal process based on the irreversibility during the compression or expansion was done. The results show that isothermal process is not so far from the reality and the power cycle can exceed other designs in terms of efficiency.*

Keywords: First law analysis; Isothermal process; Helium power cycle

1. INTRODUCTION

Today the global warming and other pollutions which are related to burning the fossil fuels are amongst the most important topics of interest. Kyoto protocol [1] and Paris agreement [2] are great examples of global community's desire to control the emission of greenhouse gases. However, desire is not necessarily will. Reduction of fossil fuels' combustion and stepping towards renewable energies do not guarantee the social development and the economic growth. Ever-increasing CO_2 emissions in the world [3] and USA withdrawal from the Paris agreement [2] in 2017 are obvious worrying signs. The main problems of renewable energies are locality and instability. Because of those, renewable energies cannot be used as the core of energy supply chain. The remaining option is the nuclear energy. It produces cheap and clean electricity. Nuclear waste management may not necessarily be as dangerous as portrayed [4] and nuclear disasters like Chernobyl and Fukushima are quite unlikely in future due to the past experience and advanced control systems. In 2017, around one third of the annual CO_2 emission is from electricity generation and around 15% from transportation. 5% of global carbon emission is produced by the buildings [5]. Nuclear energy not only has a great potential to replace the conventional fossil fuel power plants but also can produce inexpensive electricity for industry, domestic and transport section as an alternative to fossil fuels. Nuclear powered marine reactor is the best solution for eliminating the CO_2 production by the shipping sector [6,7]. Reversing the global warming effect also needs a large quantity of inexpensive clean electricity which can be supplied by nuclear power. Atmospheric CO_2 capture and Fuel-from-Air are the examples that their feasibility relays on electricity [8,9].

Generation IV reactors are novel concepts which focus on better safety, waste management, stability, versatility, economy, energy conversion, modularity and power-to-weight ratio than previous generations. Unlike conventional reactors, they operate in much higher temperature which in turn increase the thermal efficiency of power cycle [10]. Generation IV reactor will be able to accept a variable set of nuclear fuels such as Thorium which will last for many centuries [11]. Among Generation IV reactors, Very-high-temperature reactor (VHTR), Gas-cooled fast reactor (GFR) and Dual fluid reactor (DFR) can reach output temperatures up to 1000°C.

At those temperatures, selecting a proper coolant for the reactor is crucial. Molten salts and Helium (He) are considered to be the best options. Helium has had a better acceptance among the specialists. The final mass of the system will be reduced due to low density of Helium. Helium is far more difficult to be contaminated by the fuel. It can be used as the working fluid of the power cycle which further simplifies the operation and maintenance. Its high energy density and strong heat transfer characteristics is a great positive point for the designers [12]. Inertness of Helium makes it a perfect choice for Fusion reactors' cooling [13]. It is worthy of mention that fusion reactors are predicted to have many positive points of Generation IV reactors. However, helium shortage in the industrial sector and its ever-rising price maybe a limitation to its utilization [14].

Ideally, the Carnot cycle has the highest thermal efficiency among the power cycle. Despite the fact that the Carnot efficiency is unreachable, and the Carnot cycle remains on the paper, some attempts have been done to reduce the gap between the real power production and ideal efficiency. Stirling engine and Ericsson cycle are example of those attempts [15] with isothermal expansion and compression as the core phenomena. Comparing to other processes in the same range of pressure change, isothermal expansion produces the largest possible work, and the isothermal compression requires the least amount of work. The temperature difference between the expansion and compression output makes a perfect potential for regeneration which leads to a great energy saving. Igobo and Davies [16] explained the possibility and challenges of isothermal process. Isothermal process has been a challenging idea, but this has started to change. New super-alloys have unique mechanical and heat transfer characteristics and are becoming more available. Computer aided design (CAD) constantly improves the design of turbomachinery. Compressors have cooled blades and core and turbines equipped with magnetic levitation bearings which limits the need for cooling of lubricants so the turbine can be heated up by an external heat source [17,18].

Helium seems to be a proper working fluid for the isothermal process. Multi-stage axial turbomachinery for helium has identical blade size for all of stages [12]. This makes the approximation of one continuous process with many smaller processes more accurate.

An isothermal process can be estimated by a pseudo-isothermal (quasi-isothermal) process. Pseudo-isothermal process includes many partial adiabatic and then isobaric heat transfer stages. Many previous studies about analysis of pseudo-isothermal process agreed that the partial adiabatic process cannot be isentropic [15,16]. However, all of them accepted that the isobaric heat transfer after the adiabatic process is ideal and the fluid is heated up/cooled down to the inlet temperature of turbine/compressor [18,19,20,21,22,23]. This paper strongly rejects this assumption. In an ideal isothermal process, heat and work constantly affected the control volume for an infinite time. In this state, the process becomes reversible and heat resistance of the mediums border becomes irrelevant. However, after sectioning of process, the heat transfer characteristics of each section comes into calculation and infinite number of sections illustrate the infinite time. This study proved this statement. Also, this study for the first time uses the non-ideal thermophysical properties of Helium which will be more reliable in future.

2. SIMULATION

This study designs a novel Ericsson cycle with pseudo-isothermal processes. Fig.1 presents the schematics of the cycle. There are six processes in the cycle:

1→2: Pseudo-isothermal compression; Increasing the pressure with constant cooling and asserting the work

2→3: Isobaric regeneration; Isobaric heating in the cold side of recuperator

3→4: Isobaric heating; The working fluid is heated up with the coolant from the heat source which is in this case an HTR

4→5: Pseudo-isothermal expansion; Decreasing the pressure due to work production with continues heating from the heat source

5→6: Isobaric regeneration; Isobaric cooling in the hot side of recuperator

6→1: Isobaric cooling; The working fluid is cooled down with the coolant from the heat sink

The first law of thermodynamic for a control volume:

$$\dot{Q}_{net,in} - \dot{W}_{net,in} = \frac{d}{dt}\int_{CV}\left(u + \frac{V^2}{2} + gz\right)\rho d\forall + \int_{CS}\left(\frac{P}{\rho} + u + \frac{V^2}{2} + gz\right)\rho(\vec{V_r}.\vec{n})dA \qquad (1)$$

For a steady-state steady-flow control volume with single input and output and negligible kinetic and potential energy and one heat and work exchange:

$$q - w = h_{out} - h_{in} \qquad (2)$$

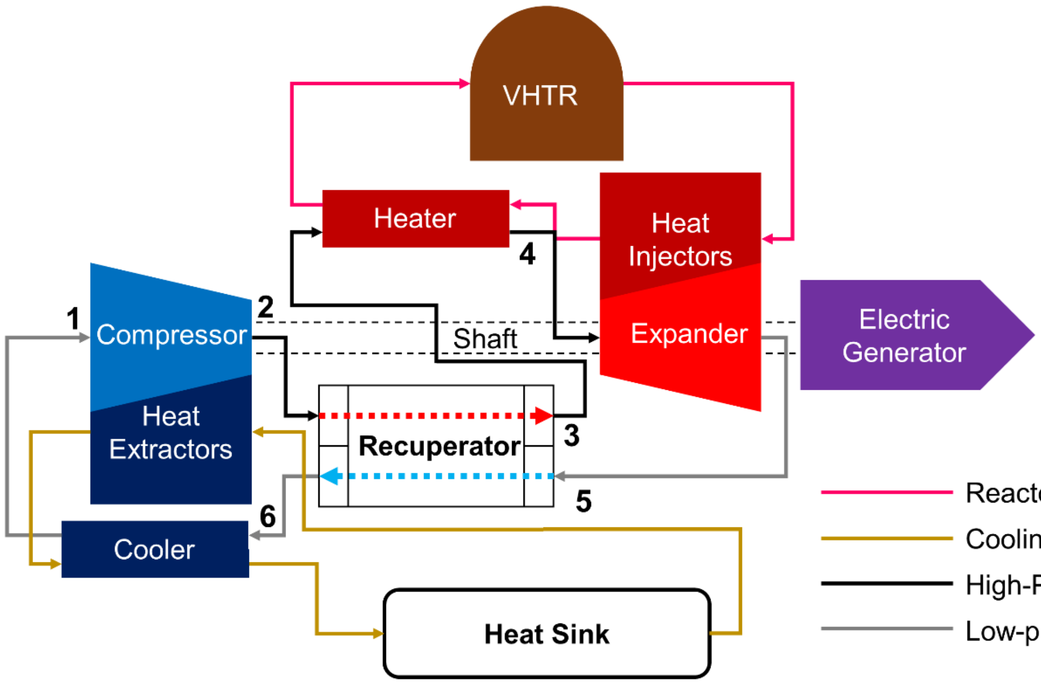

Fig. 1. Simple schematics of the designed cycle

2.1. Pseudo-isothermal Compression and Expansion

For the ideal reversible isothermal process:

$$q_{iso,id} = T_{in}(s_{out} - s_{in}) \qquad (3)$$

$$w_{iso,id} = q_{iso,id} - h_{out} + h_{in} \qquad (4)$$

Fig. 2. Shows the simulation of isothermal process. The isothermal expander (turbine) can be visualized as a set

of adiabatic expanders with interstage heater after each section. The sum of work in the adiabatic expanders are the real work output of the expander. The sum of heat in the interstage heaters is the real transferred heat to the expander. The same model can be explained for the compression. Heat injectors are the set of interstage heaters and heat extractors are the set of interstage intercoolers. In a helium isothermal axial flow turbine or compressor, the sectioning is assumed (in this paper) that each rotating stage is an adiabatic process. After that the heat exchange will happen in static blades by heat exchangers or fins.

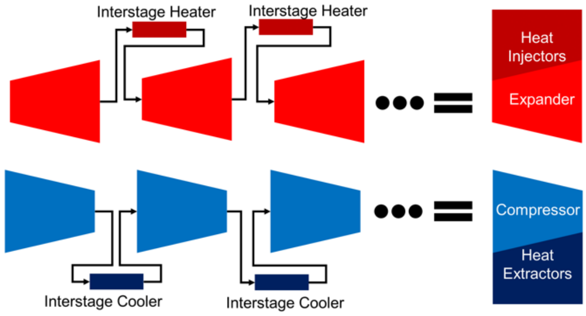

Fig. 2. Estimation of isothermal process with a set of adiabatic processes and isobaric heat transfer. Top: Expansion Bottom: Compression

Pressure at each stage:

$$\Delta P = \frac{P_{out} - P_{in}}{N} \quad (5)$$

$$P_{i.in} = (i-1)\Delta P \quad (6)$$

$$P_{i.out} = i\Delta P \quad (7)$$

Adiabatic process has an isentropic efficiency and interstage heater/cooler has an effectiveness. Ideal heat transfer happened if the outlet flow of the adiabatic turbomachine reaches the inlet temperature of expander/compressor.

Energy balance for the compression:

$$h_{i,out} = h_{i,in} + \frac{\left(h@P_{i.out}\&s_{i,in}\right) - h_{i,in}}{\eta_{ise}} \quad (8)$$

$$h_{i+1,in} = h_{i,out} - \left(h_{i,out} - h@P_{i+1.in}\&T_{in}\right)\varepsilon \quad (9)$$

Energy balance for the expansion:

$$h_{i,out} = h_{i,in} - \left(h_{i,in} - \left(h@P_{i.out}\&s_{i,in}\right)\right)\eta_{ise} \quad (10)$$

$$h_{i+1,in} = h_{i,out} + \left(\left(h@P_{i+1.in}\&T_{in}\right) - h_{i,out}\right)\varepsilon \quad (11)$$

Summing up the partial works and heats:

$$q_{iso,real} = \sum_{i=1}^{N-1}\left(h_{i+1,in} - h_{i,out}\right) \quad (12)$$

$$w_{iso,real} = \sum_{i=1}^{N}\left(h_{i,out} - h_{i,in}\right) \quad (13)$$

Note that the heat exchange at the last section is not calculated. In a real isothermal process the discharge temperature cannot be the same as the inlet temperature even if the heat transfer effectiveness is 1.

At last, it is good to know how far the real process is from the ideal. Isothermal efficiency of expansion:

$$\eta_{iso} = \frac{w_{iso,real}}{w_{iso,id}} \times 100 \quad (14)$$

For the compression:

$$\eta_{iso} = \frac{w_{iso,id}}{w_{iso,real}} \times 100 \quad (15)$$

2.2. Recuperation

Recuperator is a heat exchanger which allows the turbines discharge heats up the compressor discharge. It helps the cycle regenerate. In other words, it saves energy. Like every other heat exchanger, recuperator has an effectiveness. The heat capacity of state #2 is slightly higher than #3. So, the energy balance of the recuperator is:

$$\Gamma = \frac{h_{\#6} - h_{\#5}}{h_{\#6} - h@P_{\#6}\&T_{\#2}} = \frac{h_{\#3} - h_{\#2}}{h_{\#6} - h@P_{\#6}\&T_{\#2}} \quad (16)$$

After this, all of the state points in the cycle can be calculated. The thermal, Carnot and the second law efficiency of cycle is:

$$\eta_{thermal} = \frac{w_{iso,real,exp} - w_{iso,comp}}{h_{\#4} - h_{\#3} + q_{iso,real,exp}} \times 100 \quad (17)$$

$$\eta_{carnot} = \left(1 - \frac{T_{\#1}}{T_{\#4}}\right) \times 100 \quad (18)$$

$$\eta_{II} = \frac{\eta_{thermal}}{\eta_{carnot}} \times 100 \quad (19)$$

The thermophysical properties of Helium is derived from [24]. According to simulation of Canière et al. [25], the effectiveness of intercooler can be 0.4 or 0.7 for similar situation of this cycle. To be on the pessimistic side, 0.4 was selected as the effectiveness interstage cooler/heater. The isentropic efficiency of partial compressors, the isentropic efficiency of partial expanders and effectiveness of recuperator are 0.9, 0.92 and 0.95 [26] respectively. Again from [26] the number of stages for compressor and turbine and the compressor and turbine inter temperatures are 33, 11, 33°C and 850°C respectively. The optimum pressures before and after the expansion was identified by using Genetic Algorithm in Python. The thermophysical properties of helium was also called in Phyton and calculated.

3. RESULTS AND DISCUSSIONS

Fig. 3 shows the T-s diagram of the optimized cycle. The compressor is warped upward, and the turbine line is warped downward. This is due to adding the effectiveness to the interstage heaters/coolers. The temperature difference is more obvious in the expansion, because it has a smaller number of stages. In the compressor, the line finally converged downward due to the high number of stages.

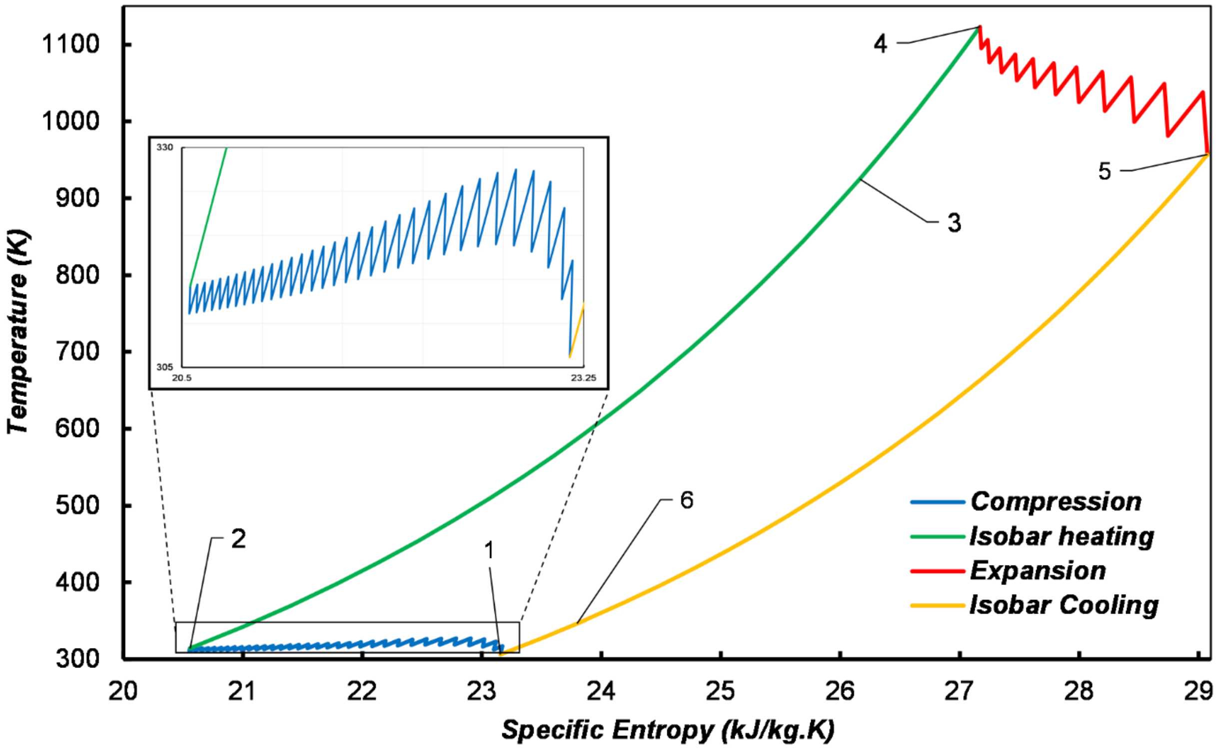

Fig. 3. T-s diagram of the optimized cycle

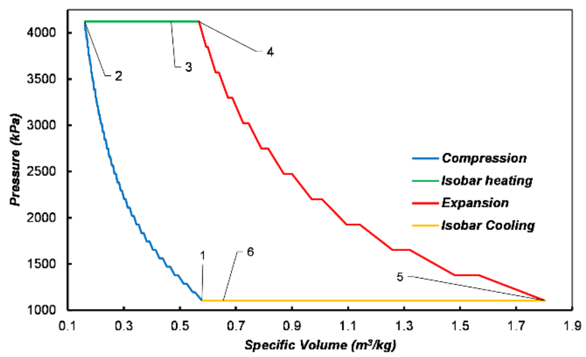

Fig. 4. P-ν diagram of the optimized cycle

Table 1. Thermophysical properties of all state point of the optimized cycle and the efficiencies

State #	T (K)	P (kPa)	s (kJ/kg)	ν (m^3/kg)
1	306.15	1104	23.15	0.58
2	314.24	4122	20.56	0.16
3	925.02	4122	26.16	0.47
4	1123.15	4122	27.17	0.57
5	956.98	1104	29.07	1.8
6	346.37	1104	23.8	0.65
$\eta_{iso,com}$	86.8%		$\eta_{thermal}$	59.29%
$\eta_{iso,exp}$	85.2%		η_{II}	81.5%

Fig. 4 is the P-ν diagram of the optimized cycle. This diagram is presented as an informatic figure. The isobar lines of each stage are noticeable. The Table 1 presents the thermodynamic properties of the cycle with the optimum pressures. It also contains the efficiencies of cycle. With the current assumptions for characteristics of the turbomachinery and the temperatures of the cycle, which seems close to reality, the thermal efficiency of almost 59% is a great advantage for this cycle. The mass flow rate of helium is around 182 kg/s for 300 MW of network.

Fig. 5 and fig. 6 show the relation between the isothermal efficiency and the number of stages, irreversibility in the partial sections and effectiveness of interstage heat transfer. Both charts show very similar trends. It is maybe due to using the helium as the working fluid. Helium has properties similar to the ideal gas and the pressure ratio of both charts are the same. The effectiveness has an impact on the isothermal efficiency, but this impact disappeared after many stages. The lesser the effectiveness is, the more stages are needed to reach near 100% isothermal efficiency. If the effectiveness is 0, the whole process become adiabatic, and result is horizontal line. This line actually proves the correctness of the code. Another reason that shows the code is right, is that all lines of effectiveness and isentropic efficiency is equal to 1 are colliding if the number of stages is 1.

Those two last figures also show that in there is any reversibility in the system, isothermal efficiency will be improved after some stages, but it will never reach 100%. It can be concluded that the irreversibility is the main reason for non-ideal isothermal process. The number of stages is also a limiting factor. A large number of stages is not possible, because it will lead to stalls in the turbine and compressor [17]. However, using more efficient parts is the key to getting close to isothermal process.

The simulation and the pressure optimization were performed with the parameters as the designed cycle with only difference was the adiabatic process in the compressor and turbine (It was done by setting the number of turbine and compressor stages as 1 or setting the effectiveness of heat extractors and heat injectors as 0). The thermal efficiency was 52.155%. Using the isothermal process increased the thermal efficiency by 13%.

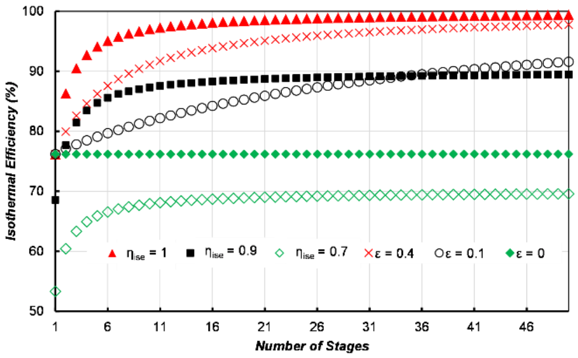

Fig. 5. Effect of number of stages on the isothermal efficiency of compression based-on isentropic efficiency of partial compressions and effectiveness of interstage coolers. The pressure and temperature are based on the optimized cycle. For the η lines the ε is 1 and for the ε lines the η is 1.

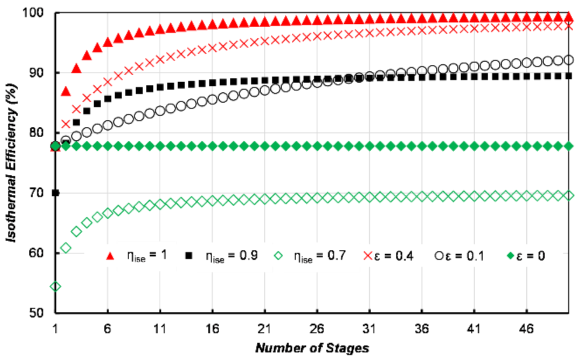

Fig. 6. Effect of number of stages on the isothermal efficiency of expansion based-on isentropic efficiency of partial compressions and effectiveness of interstage coolers. The pressure and temperature are based on the optimized cycle. For the η lines the ε is 1 and for the ε lines the η is 1.

4. CONCLUSION

In this paper, a novel and more realistic mathematical model for simulating the pseudo-isothermal compression and expansion in a helium Ericsson power cycle is presented. The cycle was designed to be coupled with Generation IV high-temperature reactors, fusion reactors or even oxy-fuel combustion system. The closed loop characteristic of this cycle makes it versatile. It was concluded that with today's current technology a highly efficient and simple power cycle with isothermal process is not so far to reach. Finally, a parametric analysis based on the irreversibility inside the turbomachinery and heat transfer effectiveness of turbomachinery was performed. It was found that the irreversibility is the main obstacle for reaching the ideal isothermal process.

5. NEXT STEP

Parametric analysis based-on temperature, second law and exergy analysis, design and CFD analysis of isothermal turbine and compressor based on current model and thermo-economy check are the future plans of this study.

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