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EXERGY ANALYSIS OF HTGR-GT

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ABSTRACT

The High Temperature Gas-cooled Reactor (HTGR) coupled with gas turbine for high efficiency in electricity production is supposed to be one of the candidates for the future nuclear power plants. The HTGR gas turbine cycle is theoretically based on the Brayton cycle with recuperated, intercooled and precooled sub-processes. In this paper, an exergy analysis of the Brayton Cycle on HTGR is presented. The analyses were done for four typical reactor outlet temperatures and the exergy loss distribution and exergy loss ratio of each sub-process was quantified. The results show that more than a half of the exergy loss takes place in the reactor, while the low pressure compressor (LPC), the high pressure compressor (HPC) and the intercooler denoted by compress system together, play a much small role in the contribution of exergy losses. With the rise of the reactor outlet temperature, both the exergy loss and exergy loss ratio of the reactor can be greatly cut down, so is the total exergy loss of the cycle; while the exergy loss ratios of the recuperator and precooler have a small rise. The total exergy efficiency of the cycle is quite high (50% more or less).

Keywords: exergy analysis; high temperature gas-cooled reactor; brayton cycle; exergy loss

1. INTRODUCTION

The Modular High Temperature Gas-cooled Reactor (MHTGR) with inherent safety and good potential of economical characteristics is considered to be one of the candidates for the future nuclear power plant [1]. Very High Temperature Gas-cooled Reactor (VHTR) is current developing trend of MHTGR, and is one of the most hopeful types for the Generation IV nuclear power system. The combination of HTGR and the power conversion unit utilizing gas turbine generator system (HTGR-GT) for high efficiency in electricity production is one of the main focuses in HTGR technology, and further more, it has a simple structure. And the projects of PBMR, GT-MHR and GTHTR300 are all designed to utilize gas turbine generator coupling with HTGR [2]. The 10MW High Temperature Gas-cooled Test Reactor (HTR-10) was built, in the Institute of Nuclear and new Energy Technology (INET), Tsinghua University, which reached its first criticality in 2000 and begun its full power operation in 2003[2]. During the 2nd International Topical Meeting on High Temperature Reactor Technology, the safety related experiments were successfully carried out openly to verify its inherent safety features. Now the subsequent project, HTR-10GT is launched to develop further technology on HTGR. In this project, the feasibility of HTGR gas turbine technology will be demonstrated by a gas turbine generator system coupled with HTR-10 reactor.

In this paper, exergy analysis is used to estimate the exergy loss distribution of the closed direct cycle.

2. BACKGROUND

The second law of thermodynamics states that all irreversible processes generate entropy, or reduce the input exergy, while increase the output anergy of the process. Exergy analysis (sometimes referred to as availability analysis), which based on the first and second law of thermodynamics, can offer an objective and quantitative criterion to evaluate these nuclear-to-electricity processes of HTGR-GT [3~10]. The criterion is used for the simultaneous assessment of the internal and external exergy losses and the performance yield of every process. Integrated processes can be optimized with regard to thermodynamic efficiencies through exergy analysis.

Exergy optimization of multi-operation processes can be difficult because of the interdependent relations between the efficiencies of individual operations. This is relevant because a thermodynamic improvement in one unit may have negative repercussions in others units. In addition, a local improvement could result into an overall degradation of the process thermodynamic performance [11].

The High Temperature Gas-cooled Reactor (HTGR) and the gas turbine (GT) generator can be practically combined in various schemes, such as closed direct cycle, closed indirect cycle and open indirect cycle. And the closed direct cycle is supposed to be the most hopeful one as the development in limitation of temperature of materials.

Fig. 1 is the schematic diagram of HTGR gas turbine closed direct cycle. High temperature and high pressure helium from the reactor core flows into the turbine directly to rotate the turbine by gas expansion. The turbine drives the generator to supply electric power and compressors to increase the helium gas pressure. The turbine exhaust gas becomes low pressure and low temperature helium after flowing through the recuperator and precooler, and then is compressed by two-stage compressors system with intercooler. This high pressure and low temperature helium is heated in recuperator by the exhaust gas of the turbine with high temperature [12]. Finally the helium flows into the reactor core again to be heated to repeat the thermodynamic cycle [2].

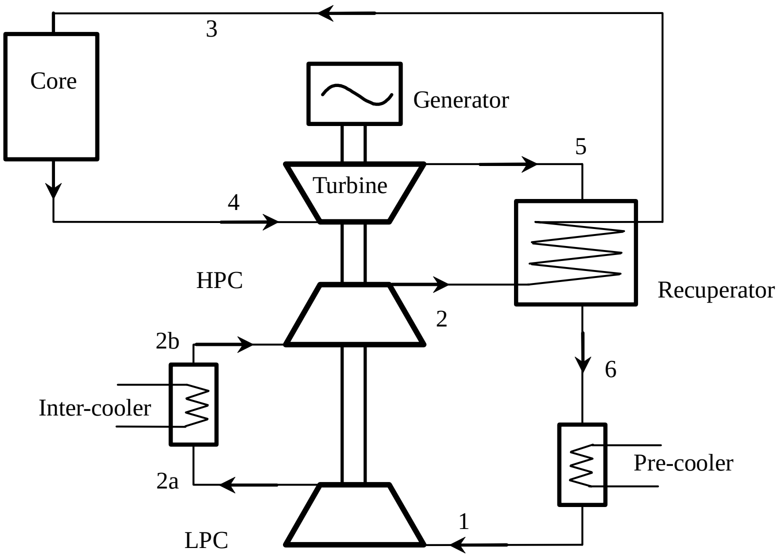

Figure 1. Closed direct cycle

The thermodynamic analysis of HTGR gas turbine cycle is theoretically based on the real Brayton cycle with recuperator, intercooler and precooler. Its T-S diagram is illustrated in Fig. 2.

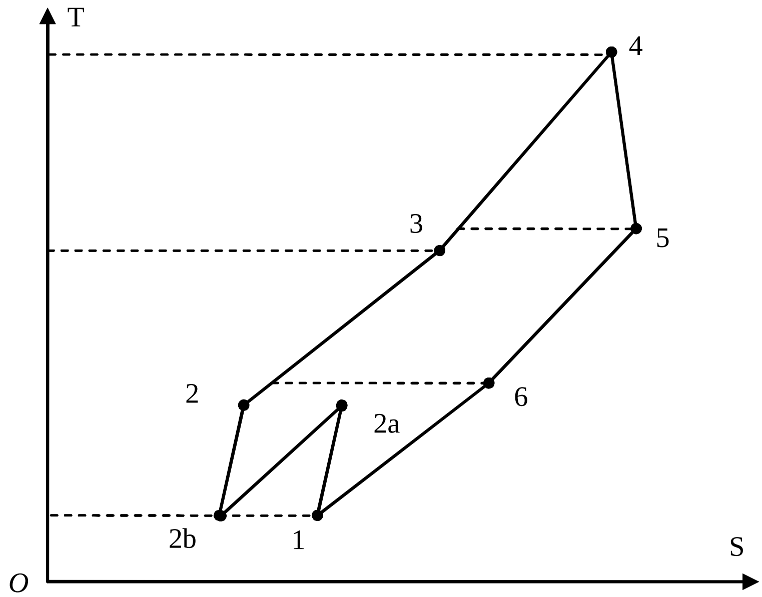

Figure 2. T-S diagram of Brayton Cycle

3. CALCULATIONS

As shown in Fig. 2, the Brayton cycle has eight sub-processes, and it's supposed that, the expansion and compression sub-processes are working processes without heat transfer and the other sub-processes are heat-transfer processes without work output. There is no mechanical loss. The temperature and pressure of environment and mass flow of the cycle are supposed to be 298K, 0.1MPa and 176Kg/s respectively. The exergy efficiency is defined as exergy content of what the processes produce purposely (denoted by E_{x1}) divided by the exergy content of all input working fluid, heat and work (denoted by E_{x2}). So the exergy loss of each sub-process is shown as follow:

$$E_{xli} = E_{x1i} - E_{x2i} \qquad ,i=1,2,\cdots\cdots \tag{1}$$

And exergy loss efficiency can be calculated by Eq. 2.

$$\varepsilon_i = \frac{E_{xli}}{Q_{Core}} \times 100\% \tag{2}$$

Exergy loss ratio is defined as exergy loss of a sub-process divided by the total exergy loss of the cycle.

$$d_i = \frac{E_{xli}}{\sum E_{xli}} \times 100\% \tag{2}$$

In the reactor core, the nuclear power is supposed to be entirely converted to heat, and there is no heat loss during heat transfer. The exergy content produced by the turbine is its internal power. Heat is assumed to be entirely transferred from helium of the low pressure side to that of the high pressure side of the recuperator driven by temperature difference. As is described in Fig. 1, the heat is rejected to the environment directly in both precooler and intercooler, and only the consumed exergy contents need to be calculated. During the compressing processes, the helium is compressed to increase its exergy by the compressors. So the power of the compressor is the input exergy content, while the rise of the exergy of the helium is the produced exergy content.

Then E_{x1}, E_{x2} and E_{xl} of each sub-process are calculated as shown in table 1.

Table 1 E_{x1} and E_{x2} of each sub-process

Sub-process	E_{x1}	E_{x2}	$E_{xl} = E_{x1} - E_{x2}$
Reactor	$G(h_4 - h_3)$	$G(h_4 - h_3 - T_0(s_4 - s_3))$	$GT_0(s_4 - s_3)$
Turbine	$G(h_4 - h_5 - T_0(s_4 - s_5))$	$G(h_4 - h_5)$	$-GT_0(s_4 - s_5)$
Recuperator	$G(h_5 - h_6 - T_0(s_5 - s_6))$	$G(h_3 - h_2 - T_0(s_3 - s_2))$	$GT_0(s_3 - s_2 - s_5 + s_6)$
Precooler	$G(h_6 - h_1 - T_0(s_6 - s_1))$	0	$G(h_6 - h_1 - T_0(s_6 - s_1))$
Low Pressure Compressor	$G(h_{2a} - h_1)$	$G(h_{2a} - h_1 - T_0(s_{2a} - s_1))$	$GT_0(s_{2a} - s_1)$
Intercooler	$G(h_{2a} - h_{2b} - T_0(s_{2a} - s_{2b}))$	0	$G(h_{2a} - h_{2b} - T_0(s_{2a} - s_{2b})$
High Pressure Compressor	$G(h_2 - h_{2b})$	$G(h_2 - h_{2b} - T_0(s_2 - s_{2b}))$	$GT_0(s_2 - s_{2b})$

4. RESULTS

According to present status of engineering technology, working conditions of the Brayton Cycle, as a conservative estimation, is given in Table 2.

Table 2 Working conditions of the Brayton Cycle on HTGR

Parameter	Signification	Value
T_0 (K)	Environmental temperature	298
P_0 (MPa)	Environment pressure	0.1
T_1 (K)	Precooler outlet temperature	308
P_2 (MPa)	High Pressure Compressor outlet pressure	7
T_3 (K)	Reactor inlet temperature	823
α (%)	recuperation effectiveness	95
φ	Isentropic index of helium	0.401[13]
η_t (%)	Isentropic efficiency of turbine	90
η_c (%)	Isentropic efficiency of compressor	89
ξ (%)	Pressure loss coefficient of the cycle	5

The total exergy losses of the brayton cycle varying with the outlet temperature of the reactor are shown in Fig. 3.

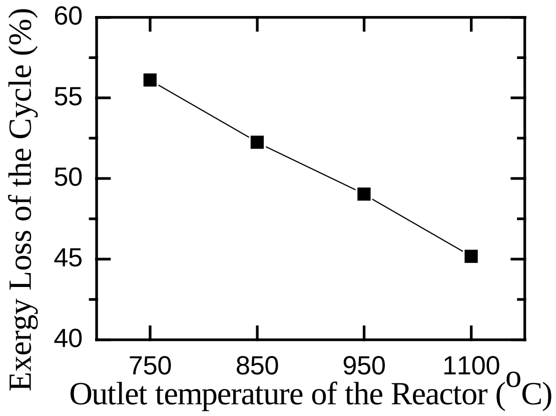

Figure 3. The influence of outlet temperature of the reactor on the exergy loss of the Brayton Cycle

The exergy loss distribution is shown for each sub-process of the cycle, see Fig. 4, given in percent ratio. The paper calculated in four typical conditions mainly different in reactor outlet temperatures.

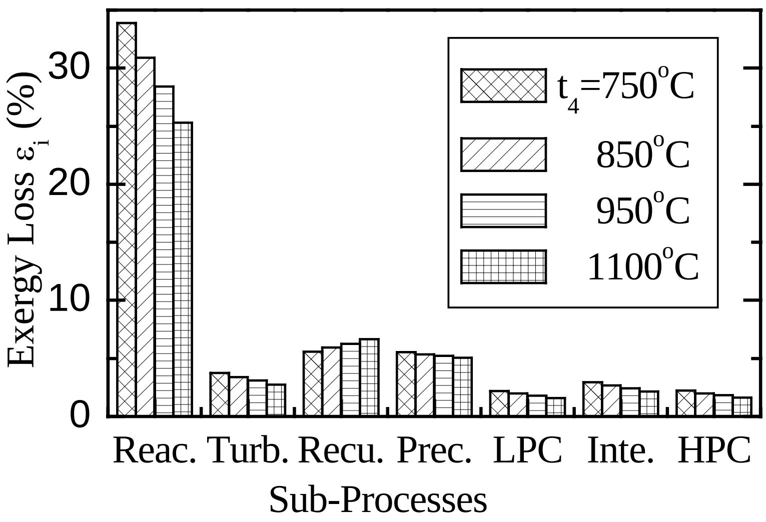

Figure 4. The exergy loss distribution of the Brayton Cycle

Exergy loss ratios of each sub-process were calculated to find the relationship between the core outlet temperature and relative contribution of exergy loss within the cycle.

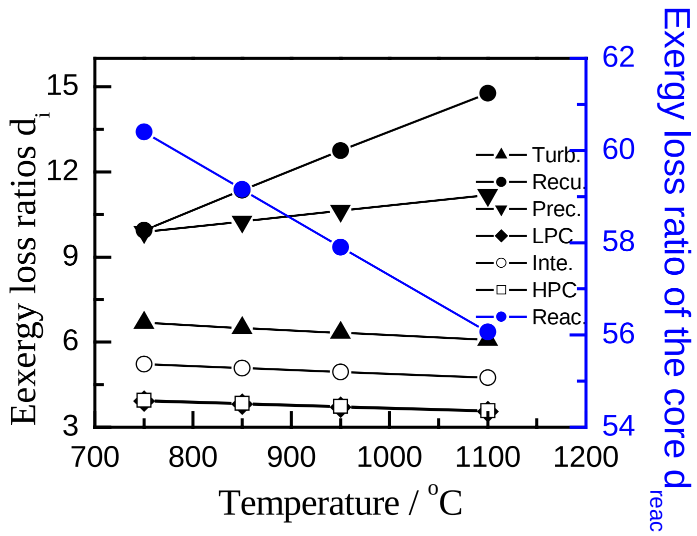

Figure 5. Exergy loss ratios of each sup-process

5. DISCUSSION

More than 50% of the exergy loss in the Brayton Cycle on HTGR under the conditions above takes place in the reactor, due to the conversion of nuclear energy into heat and the heat transfer between the core and the coolant by temperature difference. Moreover, the increase in the reactor outlet temperature could not only make a decrease in both exergy loss and exergy loss ratio of the core, but also result into an overall degradation of the total exergy loss of the cycle, from 56.55% at 750℃ to 45.16% at 1100℃, as shown in Fig. 3. The exergy loss of the reactor sub-process makes the biggest contribution to the reduction of the total exergy loss.

Because of the irreversible expansion of the helium, the exergy loss in the turbine must be taken into account, though it is less than that in the recuperator and precooler.

With the high recuperation efficiency of 95%, the recuperator, however, contributes the second biggest exergy loss for the cycle, see in Fig 4. It's caused by the difference of temperature of the two sides in the recuperator. Without the consideration of the pressure drop of the recuperator, the recuperation efficiency is not high enough concerning to its exergy efficiency. And the exergy loss of this sub-process slightly increases with the rise of the reactor outlet temperature, while its exergy loss ratio makes the biggest increase.

Although both the precooler and intercooler reject heat to the environment directly without any recovery, the exergy loss of the former is much bigger, mainly due to that the inlet temperature (T_6) of precooler is a little higher than that (T_{2a}) of the intercooler. And what's more, the exergy loss ratio of the precooler is the other one which increases with the rise of the reactor outlet temperature except the recuperator.

It is approximately equal between the LPC and HPC in the contribution of exergy loss, both due to irreversible compression. They play such an unimportant role in the contribution the exergy loss of the cycle that even the total exergy loss of the whole intercooled two-compressors set is approximately equal to, if not less than, that in the sub-process of the recuperator. And the exergy loss ratios of the LPC, HPC and intercooler have an almost the same trend of decreasing with the rise of the reactor outlet temperature.

6. CONCLUSIONS

The exergy analysis on closed Brayton Cycle coupled with HTGR has been presented for four typical reactor outlet temperatures. The results show that, exergy analysis is a useful method to evaluate the thermodynamic efficiencies and especially good at finding out the weak sub-processes of the system compared with the traditional energy analysis only based on the first law of thermodynamics. It's indicated that the exergy loss efficiency of the cycle can be greatly reduced with a higher reactor outlet temperature; the biggest exergy loss takes place in the conversion process of nuclear energy to heat in the reactor. Except the reactor, the recuperator and the precooler play much more important roles in exergy losses than other sub-processes; there is little potential for reduction of the exergy losses in LPC, intercooler or HPC; the recuperator and precooler are the only two sub-processes that increase, while that of the reactor makes the biggest decrease, with the rise of the reactor outlet temperature; whatever, the exergy efficiency of the Brayton Cycle on HTGR is quite high (50% more or less).

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