Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Cycle analysis and economic evaluation of heat pipe cooled microreactor and comparison with other power generation systems

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1. Introduction

Microreactors have recently attracted attention in that they can reduce construction costs and construction time due to site flexibility and achieve high safety performance due to their high inherent safety [1]. The microreactors have an electricity output of 1-30 MW_e and can be designed with a volume of about 1/100 times compared to large Nuclear Power Plants (NPPs). This small volume enables electricity supply in remote regions or isolated islands where large-grids are difficult to form, and is applied to military installations where volume is important to design such as space reactors, aircraft carriers, and nuclear submarines.

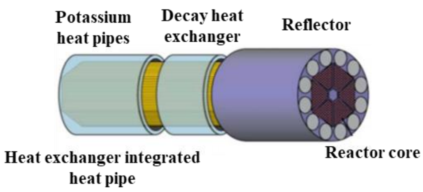
There are various reactor types applicable to the microreactors. The reactor types such as High Temperature Gas-cooled Reactor (HTGR) and Very High Temperature gas-cooled Reactor (VHTR) are recommended as microreactors for the purpose of hydrogen production due to high temperature conditions [2], and heat pipe cooled microreactors are recommended as a reactor type in remote regions and isolated islands where large-grid power generations are difficult to form due to large volume of power generation systems [3]. In addition, the heat pipe cooled microreactors does not require a cooling system of the primary system, so it can reduce cost and volume, and has a high negative feedback, which has the advantage of high safety of the microreactors.

Utilizing the various advantages of heat pipe cooled microreactors, many researchers have conducted design and analysis of heat pipe cooled microreactors to apply them to various systems. [4]. However, most of these researches was conducted on primary systems and heat pipes, and the researches on the detailed design of the Power Conversion System (PCS) and the economic evaluation including primary system and PCS are insufficient. In addition, there is a lack of research to evaluate whether the microreactor can be replaceable instead of other power generation systems. Therefore, the objective of this paper is to suggest the optimal operating condition of the heat pipe cooled microreactor, and to evaluate the applicability of heat pipe cooled microreactor to other power generation systems by comparing with existing power generation systems that use various sources such as bio, Combined Heat and Power (CHP), coal, fuel cell, gas, geothermal, hydrogen, lignite, nuclear, solar, and wind.

2. Heat pipe cooled microreactor and power conversion system

We selected heat pipe cooled microreactor as a primary system designed by Los Alamos National Lab (LANL) since the system is well optimized, especially in the neutronics and thermal-hydraulics. Fig. 1(a) indicates the configuration of the heat pipe cooled microreactor, which consists of heat pipe, heat exchanger integrated heat pipe, decay heat exchanger, and reactor core. The heat energy generated from the reactor core is transferred to the PCS through a heat pipe as an intermediate system [5].

In the case of the PCS, many researchers have conducted according to the various cycle layouts and working fluids [6]. Among them, the recompression Brayton cycle that uses s-CO_2 as a working fluid is most suitable for heat pipe cooled microreactor because it is possible to have high cycle efficiency by utilizing the high boiling temperature of the potassium in heat pipe, and the volume of turbomachinery can be reduced by utilizing the high density of s-CO_2. Therefore, we determined s-CO_2 recompression Brayton cycle as a PCS of the heat pipe cooled microreactor. Additionally, the components of the PCS including turbomachinery and heat exchangers were selected as radial type single-stage turbine and Printed Circuit Heat Exchanger (PCHE) considering the operating conditions of high temperature and pressure [6].



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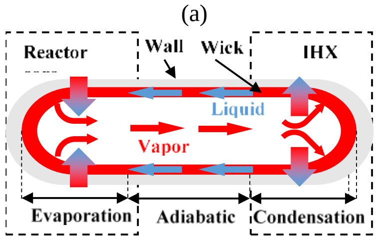

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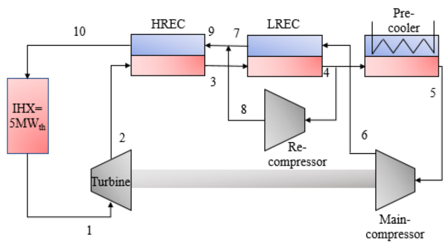
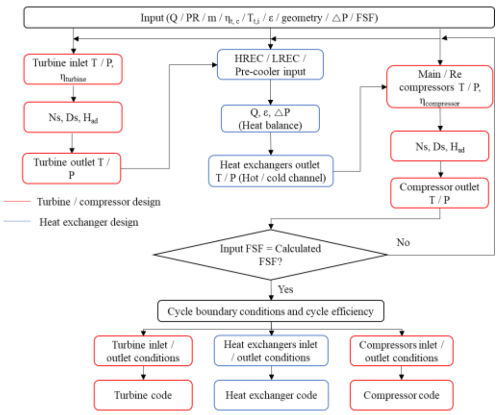


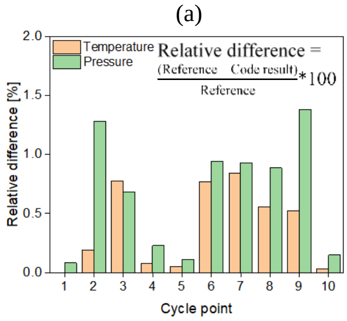
(c)
Fig. 1. Heat pipe cooled microreactor
(a) Primary system [5] (b) Heat pipe (c) s-CO_2 recompression Brayton cycle

3. Development and validation of cycle analysis code

In order to evaluate cycle efficiency according to the design parameters, we developed the cycle code that included turbomachinery and heat exchanger design codes. This cycle code is calculated for the temperature, pressure, and mass flow rate at each design point through energy balance, and the heat transfer areas (volumes) of heat exchangers and diameters of turbomachinery are calculated to match these calculated values (temperature, pressure, and mass flow rate) in the cycle code. The design of heat exchanger is conducted through the Kern's method, and the turbomachinery is designed using the N_s-D_s diagram [7, 8]. We performed comparisons with existing literature to determine whether the results of the developed code are reasonable [6]. As a result of comparison, the maximum relative difference between the results of the reference case and those calculated using the developed code is approximately 1.4% as shown in Fig. 2(b).



(a)



(b)

Fig. 2. Cycle analysis code (a) Flowchart (b) Validation [6]

4. Result and discussion

To understand the change in cycle efficiency according to the design parameters, we calculated cycle efficiency according to the mass flow rate, pressure ratio, effectiveness of heat exchangers, and Turbine Inlet Temperature (TIT). In addition, we calculated the economics of heat pipe cooled microreactor to evaluate the applicability of designed microreactor with maximum cycle efficiency instead of other power generation systems.

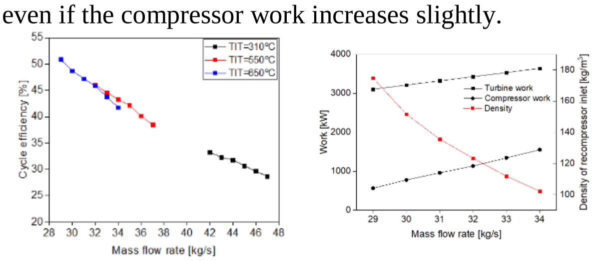
4.1 Cycle efficiency according to the cycle parameters

Fig. 3(a) indicates that cycle efficiency decreases as the mass flow rate increases because the increase rate in compressor work is larger than that in turbine work. An increase in the mass flow rate increases the temperature at the recompressor inlet, thereby reducing density of CO_2 as depicted in Fig. 3(b). The decrease in the density increases compressor work (W=Q*△P).

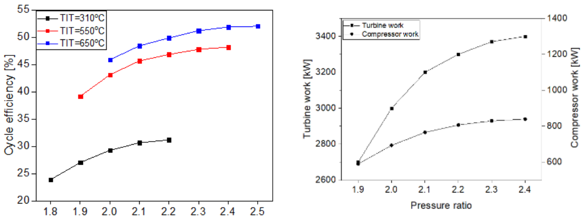
Fig. 4(a) shows cycle efficiency according to the pressure ratio. As the pressure ratio increases, the cycle efficiency increases. However, the cycle efficiency does not increase constantly even if the pressure ratio continuously increases. This is because the increase rates of turbine work and compressor work are almost similar under the high pressure ratio condition, so the net work and cycle efficiency are almost constant.

In the case of the effectiveness of heat exchangers, the increase in effectiveness increases cycle efficiency. The increase in effectiveness improves the heat transfer performance of the LREC and reduces the temperature of CO_2 at the recompressor inlet. Due to decrease in the temperature, the density of the fluid increases and the recompressor work decreases as shown in Fig. 5(b).

In addition, it can be seen that the higher the TIT, the higher the cycle efficiency under all conditions. The increase in turbine inlet temperature increases turbine work because the enthalpy drop in the turbine increases even if the compressor work increases slightly.

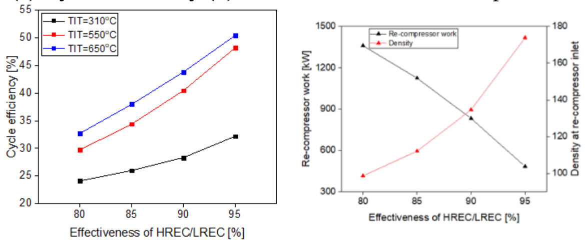


(a) (b)
Fig. 3. Cycle efficiency according to the mass flow rate
(a) Cycle efficiency (b) Works of turbine and compressor



(a) (b)

Fig. 4. Cycle efficiency according to the pressure ratio
(a) Cycle efficiency (b) Works of turbine and compressor

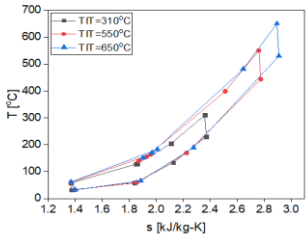


(a) (b)

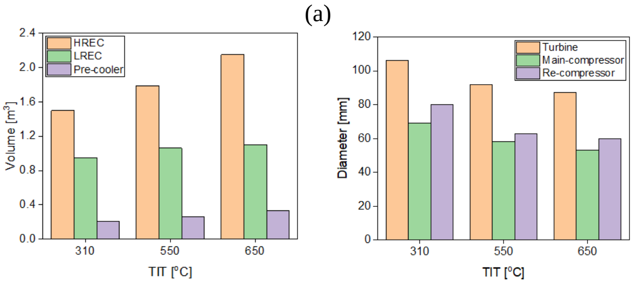
Fig. 5. Cycle efficiency according to the effectiveness of heat exchangers
(a) Cycle efficiency (b) Work of compressor

4.2 Optimal operating conditions and volume of each component

Based on the cycle analysis according to the design parameters, we derived optimal operating conditions with maximum cycle efficiency under three TIT conditions. Fig. 6(a) indicates T-s diagram of optimal operating conditions, and the cycle efficiency corresponds to 31.2%, 47.2%, and 52.0% under the 310℃, 550℃, and 650℃ of TIT conditions, respectively. Figs. 6(b) and 6(c) show volumes of heat exchangers and diameters of turbomachinery under optimal operating conditions. Under all TIT conditions, the volumes of HRECs and diameters of turbines are the largest because HREC's heat transfer rate and turbine work are the largest. In this regard, the designs of HREC and turbine in the microreactor where volume is important is one of the crucial factors.



(a)



(b) (c)

Fig. 6. Optimal operating conditions

(a) T-s diagram (b) Volumes of heat exchangers (c) Diameters of turbomachinery

4.3 Economic evaluation and comparison with other power generation systems

To evaluate the applicability of microreactor as power generation system, the economic evaluation was performed at the maximum cycle efficiency condition based on the Levelized Cost Of Electricity (LCOE), which is the total cost including initial and operating costs per the amount of electricity produced during the plant lifetime. In the case of the primary system, we used the normalized cost for heat pipe cooled microreactors suggested by the Idaho National Lab (INL) [9]. For PCS, The costs of turbomachinery and heat exchangers were calculated by Equations (2)-(4) [10].

$$\mathrm{LCOE} = \frac{Capital\ cost + \sum_{i=1}^{y}(O\&M\ cost + Fuel\ cost)/(1+r)^y}{\sum_{i=1}^{y}(Electricity\ energy)/(1+r)^y} \quad (1)$$

$$C_t = 479.34 m \cdot [1/(0.93-\eta_t)] \cdot \ln(PR) \cdot [1+\exp(0.036 \cdot T_i - 54.4)] \quad (2)$$

$$C_c = 71.1 \cdot m \cdot [1/(0.92-\eta_c)] \cdot (PR) \cdot \ln(PR) \quad (3)$$

$$C_{PCHE} = C_M \cdot (V \cdot \rho) \quad (4)$$

Based on the designed microreactor, we derived the LCOE of 83 USD/MWh. Fig.7 indicates the LCOE according to the sources of power generation systems [11]. When generating the same amount of electricity, the total cost of large nuclear power plant was the cheapest, and that of fuel cell was the most expensive In general, nuclear power plants are expensive to build but relatively cheap to run because of the high energy density of uranium and the low operating cost (consumption of fuel). As shown in Fig. 7 and Table II, economics of microreactor is cheaper or similar than most power generation systems except large nuclear power plant. In this regard, the designed microreactor is considered to be able to replace other power generation systems.

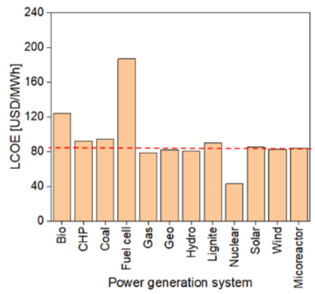


Fig. 7. LCOE according to the power generation systems [11]

Table I. Optimal operating conditions when TIT is 650℃

Points	1	2	3	4	5
T (℃)	650	530.1	189.1	66.1	32
P (kPa)	19000	7600	7572.4	7541.1	7540.5
m (kg/s)	24	24	24	24	15.2
Points	6	7	8	9	10
T (℃)	61.7	182.7	151.6	170.8	482.2

P (kPa)	19014.8	19010.2	19012	19010.2	19000
m (kg/s)	15.2	15.2	8.8	24	24

Table II. The LCOE of power generation system

Source	**Bio**	**CHP**	**Coal**	**Fuel cell**
LCOE [USD/MWh]	124	92	94	187
Source	**Gas**	**Geothermal**	**Hydrogen**	**Lignite**
LCOE [USD/MWh]	78	82	80	90
Source	**Nuclear**	**Solar**	**Wind**	**Microreactor**
LCOE [USD/MWh]	42	85	83	83

5. Conclusion

As part of researches on heat pipe cooled microreactors, cycle analysis of the microreactor was conducted according to the pressure ratio, mass flow rate, TIT, and effectiveness of heat exchangers, and we derived optimal operating conditions with maximum cycle efficiency. Based on the designed microreactor, we calculated the LCOE of microreactor, and compared the microreactor with other power generation systems using various heat sources. As a result of comparison, the microreactor was more economical or similar to produce the same amount of electricity than the existing power generation systems except large nuclear power plant. Through this result, it is expected that the heat pipe cooled microreactors can be applied instead of power generation systems using bio, CHP, coal, fuel cell, lignite, solar, and wind.

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