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Preliminary design of heater section for isothermal Turbine nuclear system

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1. Introduction

Demand for small modular reactor (SMR) is increasing for following reasons. SMR is much cheaper per unit than the existing large-scale nuclear power plants in terms of initial investment and construction costs. It has enhanced inherent safety due to the low output of the reactor. It can be coupled with various other energy technologies such as integrating with renewable energy system. It can be applied to electricity production but it is also possible for other applications such as for transport system due to its compactness. Various types of SMR are being developed around the world. HTR-PM (gas-cooled reactor type SMR, 100MWe) of INET (China), SMART (pressurized water reactor type SMR, 100MWe) of KAERI (Korea) and MMR (supercritical CO_2-cooled reactor type SMR, 10MWe) of KAIST (Korea) are in this category.

As a part of this effort, KAIST is proposing a new system called isothermal turbine nuclear system which uses S-CO_2 as the working fluid. The isothermal turbine is a concept to integrate nuclear reactor with turbine directly. The key idea is to load the fuel on the stator blade of the turbine, which creates a flow angle in the turbine to simultaneously generate heat and work in the turbine.

In 1950, the US conducted a nuclear turbojet engine study [1]. Fig.1 is a conceptual diagram of the system. The system is bulky because the reactor and turbine are separated. There is a problem that the efficiency of the cycle is lowered because the fluid heated in the reactor undergoes heat loss and pressure drop during the process of transporting energy to the turbine. Because of this issue, the integration of nuclear energy, which has the highest energy density of all energy sources, and gas turbine technology, which is the mechanical device with the highest power density, has not been successful so far. The isothermal turbine system is small in volume because the reactor and the turbine are integrated in one component. In addition, the efficiency of the cycle is expected to be high because it directly transfers the heat of the reactor without any heat exchangers.

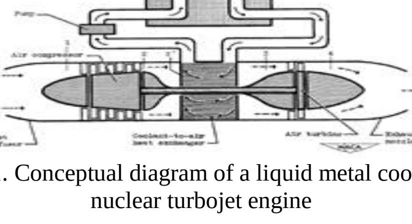

Fig.1. Conceptual diagram of a liquid metal cooling nuclear turbojet engine

A study on cycle efficiency using isothermal turbines was conducted by B.S Oh et al [2] previously. Based on the simple recuperated MMR cycle, the isothermal turbine system was compared to the conventional adiabatic turbine system. As a result, the optimized efficiency of the isothermal turbine cycle is about 2.1% higher than the conventional adiabatic turbine system.

Isothermal turbine can be different from common gas turbines because it is integral of the reactor and the turbine. Therefore, many fundamental research works are required, which encompasses from fuel composition to turbine blade design. Finally, safety studies, including radiation shield and accident, will be needed. In this study, the reactor criticality, which is the most basic of isothermal turbine design, will be discussed first, with the exception of the others.

2. Methods and results

In this study, an isothermal turbine was considered as a fast reactor so that the moderator does not make the system bulky. Thus, cross sections at 1MeV were used for the calculation. Table.1 shows the value of each cross section. At the beginning of the operation, although there will be no Pu-239, the criticality should be unity or higher. So the necessary condition for criticality with only U-235 was first checked. Fig.2 is a conceptual diagram of isothermal turbine. Green bars are stator blade containing nuclear fuels. To calculate criticality, a few assumptions were made. From two reasons, the fuel, S-CO2 and stainless-steel 304 were assumed to be homogeneously mixed. First, a reactor core is called a quasi-homogeneous reactor if the neutron mean free path at all neutron energy is large compared to the thickness of fuel rod [3]. In the case of isothermal turbine, the neutron energy and fuel enrichment may be high and the thickness of the stator blade is thin, so it is in a quasi-homogeneous form. From the standpoint of the neutrons, a quasi-homogeneous reactor is actually the same as a homogeneous reactor. Second reason is to roughly determine the geometry size of the turbine for criticality. Also, fission was assumed to occur only in U-235. Lastly, reflector was not considered.

Table.1. Neutron microscopic cross section at 1MeV

	$\sigma_\gamma(b)$	$\sigma_f(b)$	$\sigma_a(b)$	$\sigma_s(b)$	ν
$^{235}_{92}U$	0.1037	1.1992	1.3029	3.6365	2.6
$^{238}_{92}U$	0.1295	0.0142	0.1437	4.6361	0
C	0.00002	0	0.00002	2.5450	0
O	0.0001	0	0.0001	8.1019	0
Fe	0.0025	0	0.0025	1.7462	0
Ni	0.0079	0	0.0079	5.5195	0
Cr	0.0002	0	0.0002	2.7280	0

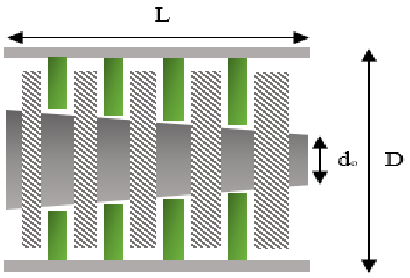

Fig.2. Conceptual diagram of isothermal turbine

2.1 One-group reactor equation

With the previous assumption, the criticality (k) and geometric buckling (B^2) can be obtained by a one-group equation for cylindrical shape reactor.

$$k = \frac{\nu\Sigma_f\phi}{DB^2\phi + \Sigma_a\phi} = \frac{\nu\Sigma_f}{DB^2 + \Sigma_a}$$

$$B^2 = (\frac{2.405}{R})^2 + (\frac{\pi}{H})^2$$

Here, ϕ represents the one-group neutron flux. D, Σ_a and Σ_f denote the one-group diffusion coefficient, the macroscopic absorption cross section for the mixture and macroscopic fission cross section for the nuclear fuel, respectively. Also, ν is the number of neutrons generated per fission, R and H are radius and height, respectively.

2.2 Turbine size study

Table.2.Isothermal turbine conditions

Turbine	Inlet pressure (MPa)	19.93
	Outlet pressure (MPa)	8.16
	Inlet temperature (℃)	550
	Outlet temperature (℃)	550

For the geometric buckling calculation, the size of the turbine should be determined. The turbine inlet, outlet conditions are adopted from previously developed KAIST MMR cycle conditions [4]. Table.2 shows the conditions. Fluid velocity is assumed to be 50m/s. Given pressures and temperatures, inlet and outlet S-CO_2 densities were obtained from NIST REFPROP. Then fluid inlet and outlet flow areas are simply calculated from the below equation.

$$\dot{m} = \rho A v$$

If the axis diameter, volume ratio and fluid flow area are known, the turbine diameter can be calculated. The volume ratio is the ratio of S-CO_2 volume to the turbine volume.

$$D = 2\sqrt{(\frac{d}{2})^2 + \frac{A}{\pi}}$$

D, d are diameters of turbine and axis, respectively. A is fluid flow area and vr is volume ratio. In this study, the axis diameter (d_o) of the turbine outlet was kept constant. The value is chosen to be 20cm. The variable which affects the turbine diameter is the volume ratio. Also, turbine length (L) is not determined. Thus, the volume ratio and turbine length finally affects the criticality.

2.3 Criticality calculation

Since the isothermal turbine is a new concept, the fuel enrichment can be different from commercial reactor enrichment and the stator blade size can be different from the stator blade size of the conventional gas turbine. Therefore, as mentioned above, the variables in the calculation are volume ratio, U-235 enrichment and turbine length in this study.

The criticality was calculated for three cases; U-235 enrichments are 5%, 10% and 30%. Figs.3, 4 and 5 show the calculation results. All three graphs show the same shape and the criticality is proportional to the turbine length and inversely proportional to the volume ratio. This means that if the turbine length increases for the same volume ratio, the criticality increases due to the increase in the amount of fuel. Also, graphs show that for the prescribed conditions, enrichment should be higher than 30% to construct a critical reactor.

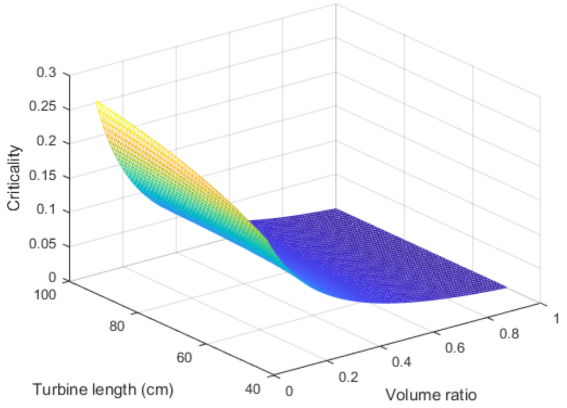

Fig.3. Criticality at 5% enrichment

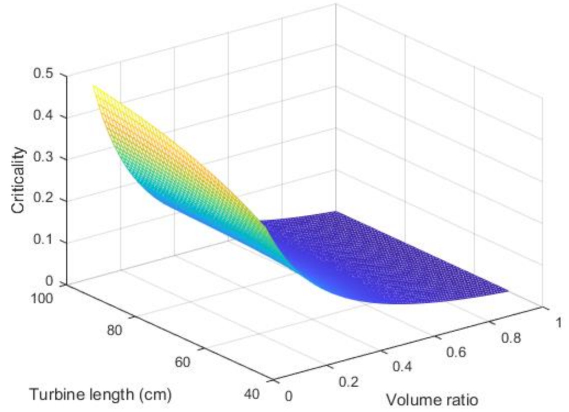

Fig.4. Criticality at 10% enrichment

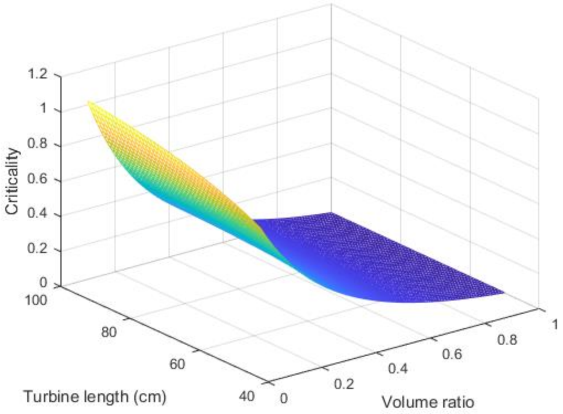

Fig.5. Criticality at 30% enrichment

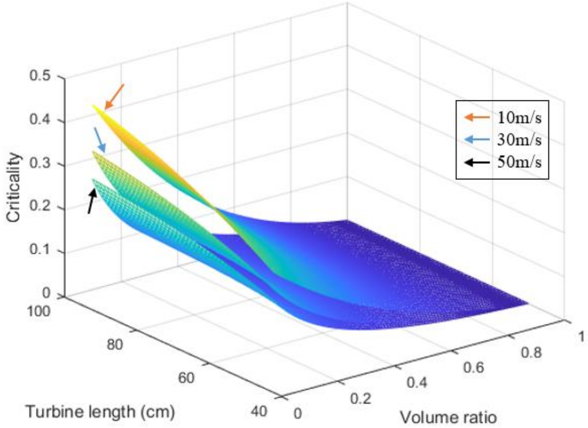

Fig.6. Criticality by fluid velocity at 5% enrichment

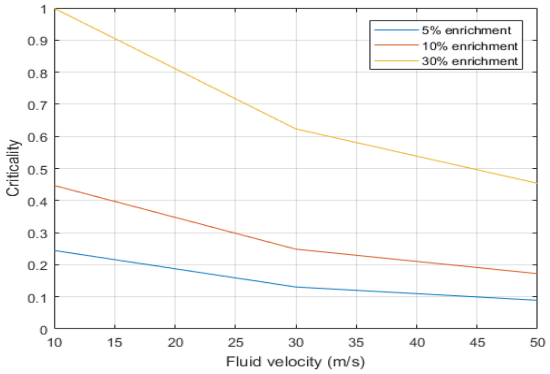

Fig.7. Degree of criticality change vs. fluid velocity in each enrichment

The effect of fluid velocity in turbine was studied. This is because fluid velocities affect the flow area of turbine which affects criticality in result. The results are shown in Fig.6. If the fluid velocity becomes slower, the flow area becomes larger, which is similar to turbine length becoming longer. Fig.7 shows that the change in criticality versus fluid velocity is greater for the higher enrichment. These results were obtained when volume ratio is 0.3 and turbine length is 100cm.

3. Summary

In this study, criticality calculation is first performed as the most basic step for isothermal turbine design. These results are preliminary because they are obtained from simple one group homogeneous model. However, based on these values, more detailed calculations for design will be performed, such as designing turbine blades or determining the number of stages. Also, without assuming homogeneous, detailed calculations of criticality will be done later using Serpent.

Reference

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