THERMAL AND STRESS ANALYSIS OF HYPER TARGET SYSTEM*

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Abstract

HYPER (*HY*brid *P*ower *E*xtraction *R*eactor) is the accelerator driven transmutation system which is being developed by KAERI (Korea Atomic Energy Research Institute). We plan to finish the preliminary design of HYPER by 2001. Pb-Bi is used as the coolant and target material of HYPER. One of the issues related to the HYPER target system is the thermal and mechanical loads imposed on the Pb-Bi and the beam window. We used LCS (LAHET Code System) to calculate heat generation. FLUENT was used for thermal-hydraulic calculation, and finally stress calculation was performed by ANSYS. A beam condition such as current varied. The initial velocity of Pb-Bi also varied.

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1. Introduction

HYPER (*HY*brid *P*ower *E*xtraction *R*eactor) is the accelerator driven transmutation system designed by KAERI (Korea Atomic Energy Research Institute) [1]. An accelerator driven system provides the possibility of reducing plutonium, minor actinides, and environmentally hazardous fission products from the nuclear waste coming from the conventional nuclear power plant. In addition, it can be used to produce electricity. HYPER is designed to transmute TRU and fission products such as ^{99}Tc and ^{129}I.

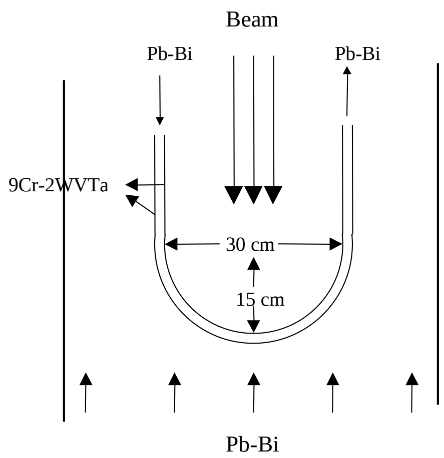
Because an accelerator driven system is a sub-critical reactor, external neutrons should be provided by a target system inside the reactor. HYPER adopts Pb-Bi as the coolant and target material, which are not separated. Some key issues related to developing target system are window and Pb-Bi cooling, corrosion, radiation damage etc. Corrosion and radiation damage degrade the performance of the beam window, and an experimental study is necessary to understand the change due to those damages. In this paper, we use simulation codes to determine the target geometry and beam conditions under which HYPER target system can be operated with stability before corrosion and radiation damage affect the beam window.

We studied the basic thermal hydraulic characteristics of the target system using FLUENT code, and we also used ANSYS code [2] to calculate the stress of the beam window. The heat generation inside beam window and Pb-Bi was calculated using LCS (LAHET Code System) [3].

2. Double window target

Figure 1 shows the structure of the target area and beam window geometry. HYPER beam channel is cylindrical and located at the centre of the reactor with a 50-cm diameter. The window is designed to have 2-mm thick steel layers, and Pb-Bi coolant flows between the two layers for window cooling. The gap width of the coolant channel is about 4 mm. The cross-section of the beam tube is 30×30 cm^2 and the window has a cylindrically curved profile.

Figure 1. **Target area and beam window geometry**



The target Pb-Bi is coming from the bottom of the beam channel and the beam is injected from the top. The Pb-Bi flow is slowed just below the centre of the beam window. Therefore Pb-Bi is forced to flow from left to right between windows.

For the beam window material, 9Cr-2WVTa was chosen since advanced martensitic/ferritic steels are better in Pb-Bi corrosion than austenitic steels and do not show a DBTT problem [4]. The yield strength of 9Cr-2WVTa is about 600 MPa at 400°C.

3. Calculation conditions

The cylindrical forced convection target system is set to be 50 cm in diameter and 100 cm in height. The bottom of the beam window is located 25 cm below the top. The initial temperature of Pb-Bi is set to be 340°C for both target and window cooling Pb-Bi. The initial velocity of window cooling Pb-Bi is 6 m/s. We separated the double window calculation from the single window calculation to simplify the calculation geometry.

The heat deposition in Pb-Bi and window is calculated using the LAHET Code System. The beam is assumed to have a circular shape with a diameter of 10 cm and a parabolic density distribution. The result shows that about 52% of the total beam energy are deposited as heat in the target zone. Figure 2 shows the heat deposition as a function of the radius from the beam centre and distance from the target surface for Pb-Bi and the window in the case of a 20 mA beam.

Figure 2. **Heat deposition rate for a 20mA beam**

Proton Beam Injection

($\times 10^9$ W/m^3)

	10cm	9cm	8cm	7cm	6cm	5cm	4cm	3cm	2cm	1cm
10cm	0.02	0.03	0.06	0.12	0.26	1.94	4.86	7.14	8.73	9.64
10cm	0.05	0.07	0.12	0.19	0.42	1.39	3.01	4.30	5.23	5.68
10cm	0.05	0.07	0.10	0.19	0.39	0.92	1.63	2.26	2.71	2.98
10cm	0.04	0.06	0.10	0.18	0.31	0.55	0.82	1.08	1.29	1.36
10cm	0.04	0.06	0.09	0.14	0.22	0.32	0.42	0.50	0.60	0.64

Proton Beam Injection

($\times 10^9$ W/m^3)

	10cm	9cm	8cm	7cm	6cm	5cm	4cm	3cm	2cm	1cm
2mm	0.004	0.006	0.009	0.019	0.071	1.90	5.29	7.20	9.09	9.64

4. 2-D calculation

The general CFD code FLUENT was used to simulate the two-dimensional thermal and flow distribution of the liquid target. Calculation analyses are performed in two-dimensional axi-symmetry cylindrical geometry. The calculation parameter is the liquid Pb-Bi inlet velocity which vary from 1.1 m/s to 2.0 m/s. The beam current and velocity of cooling Pb-Bi are fixed to 20 mA and 6 m/s respectively. In this calculation, the surfaces are set to be adiabatic boundaries. For the calculation of this study, we used an orthogonal co-ordinate transformation. This transformation is performed using the grid generation components of the FLUENT code.

Figure 3 shows the calculation geometry of the FLUENT code. The centre of the Pb-Bi beam channel is narrowed to increase the velocity of up-coming Pb-Bi so that the efficiency of window cooling is maximised.

In the single window calculation, the maximum temperature of the window is 2 277°C for an inlet velocity of 1.1 m/s and 1 808°C for an inlet velocity of 2.0 m/s in the steel beam window region. These temperatures exceed the beam window melting temperature. Therefore, this is not allowable for the steel window. Figure 4 shows the temperature distribution and the velocity vector profile of the target and the window region for an inlet velocity of 2.0 m/s. Table 1 shows the calculation result of the maximum temperature for each case. Based on these calculations, the beam window can be damaged by high temperature and thermal stress. So, the independent cooling system for the beam window must be considered.

Figure 3. **FLUENT calculation geometry for the single and double window**

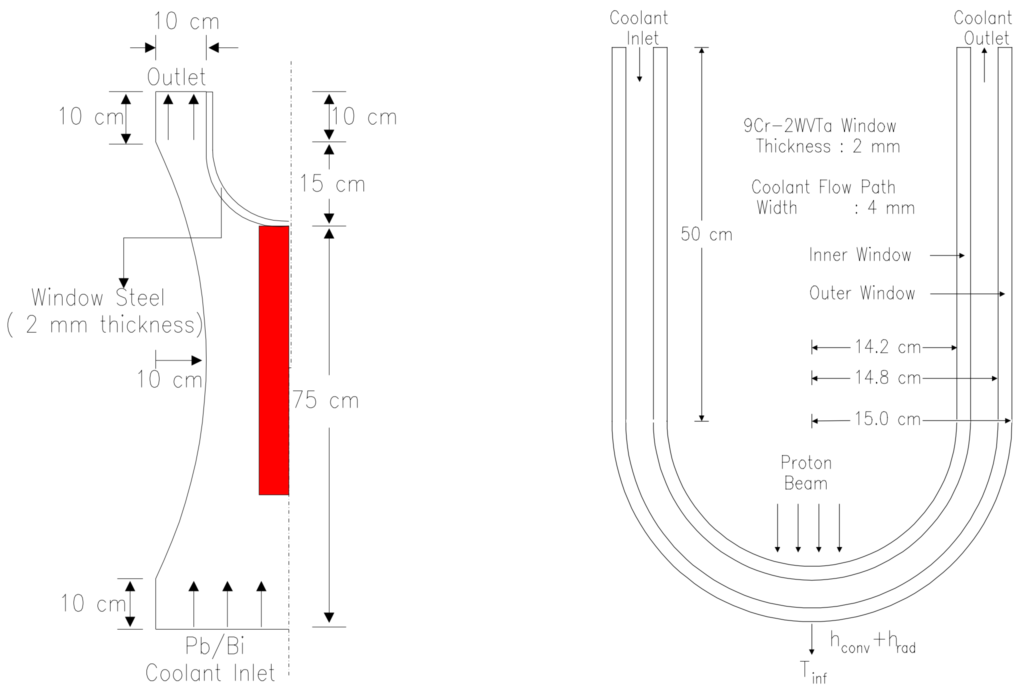


Figure 4. **Temperature and velocity distribution of the single window**

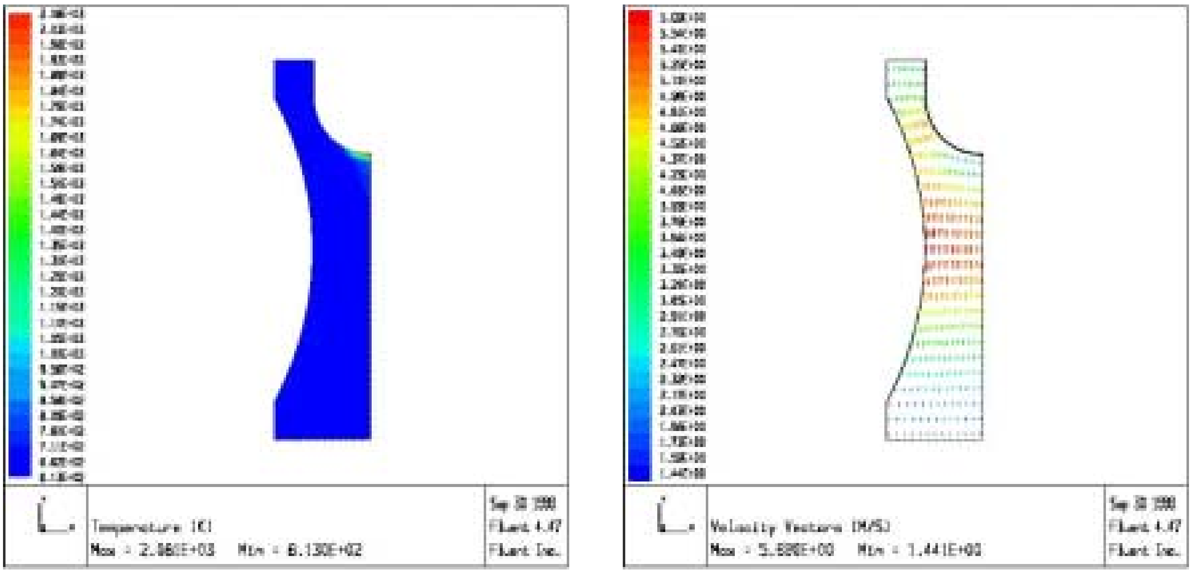


Table 1. **Maximum temperature for the single window**

Bottom inlet velocity (m/s)	1.1	1.35	1.5	2.0
Max. temp. (°C)	2 277	2 086	2 003	1 808

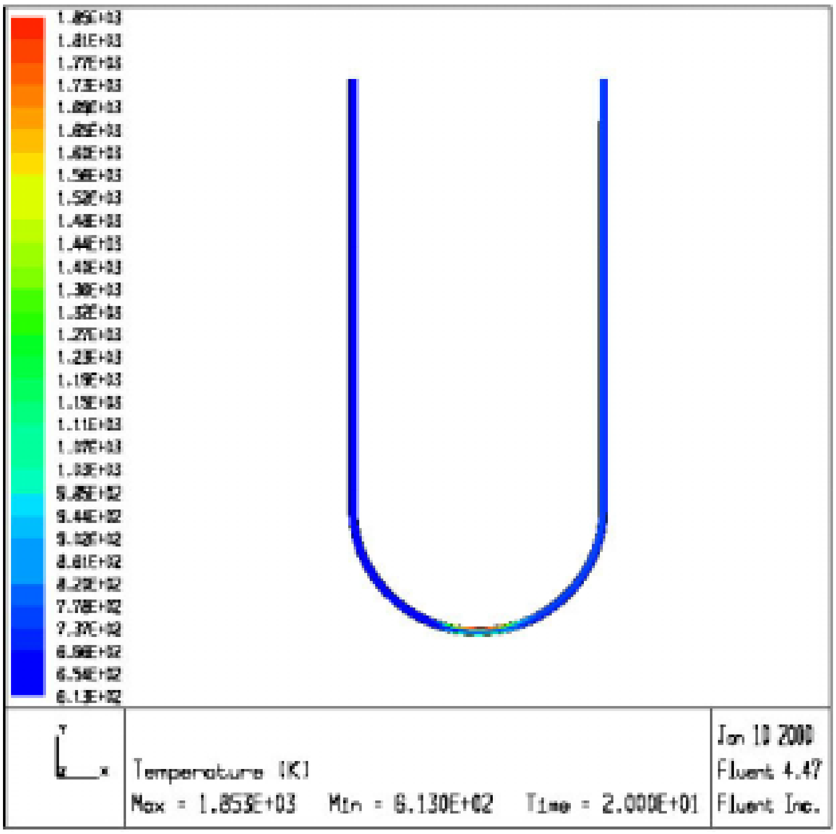
The coolant flowing direction is x-directional co-ordinate and the vertical direction of the coolant flowing is the y-directional co-ordinate. The spacing of the y-directional cells is 1 mm. We used the same heat generation rates for the inner and outer windows as shown in Figure 2. The heat transfer of the lower surface of lower window is treated by the heat transfer coefficient obtained by the calculation of the single window.

Maximum temperatures in the double windows are presented in Table 2. The maximum temperature in the inner window reaches 1 580°C. This value is higher than the window melting temperature. The inlet velocity of the Pb-Bi coolant flowing in the narrow channel must be larger than 6 m/s. As a result, the maximum temperature in the lower window reaches 1 077 °C for a 1.1 m/sec bottom inlet velocity of the single window and 927 °C for a 2.0 m/s bottom inlet velocity.

Table 2. **Maximum temperature for the double window**

Bottom inlet velocity (m/s)	1.1	1.35	1.5	2.0
Upper window (°C)	1 580	1 580	1 580	1 580
Lower window (°C)	1 077	1 027	997	927

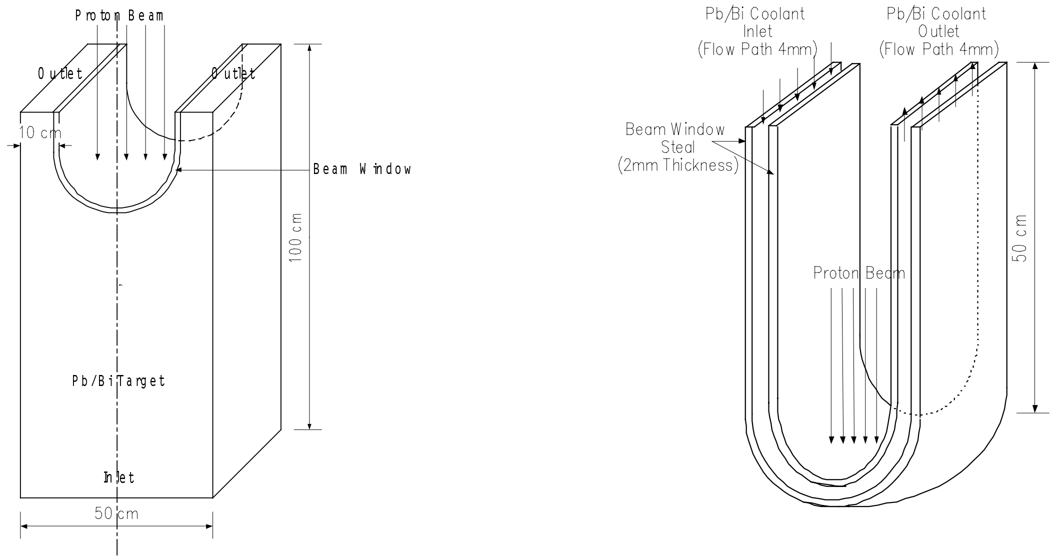
Figure 5. **Temperature distribution of the double window case**



5. 3-D calculation

Figure 6 shows target geometry for FLUENT 3-D calculations. The beam channel is assumed to be rectangular to simplify the calculation. We first calculated the temperature of the bottom Pb-Bi and the single window part and then we calculated the double window part separately. In 3-D calculations, the velocity of up-coming Pb-Bi is fixed to be 2 m/s and 3 different beam currents are used, which are 2 mA, 10 mA and 20 mA. The velocity of Pb-Bi flowing between windows is 6 m/s.

Figure 6. **Target geometry for 3-D calculation**



The maximum temperature of the single window was calculated to be 571°C in the case of a 2 mA beam. In the same case, the maximum temperature of the upper and lower window are found to be 464 and 429°C, respectively. Tables 3 and 4 show the maximum temperatures of the single and double window for 3 different beam currents.

Table 3. **Maximum temperature for the single window**

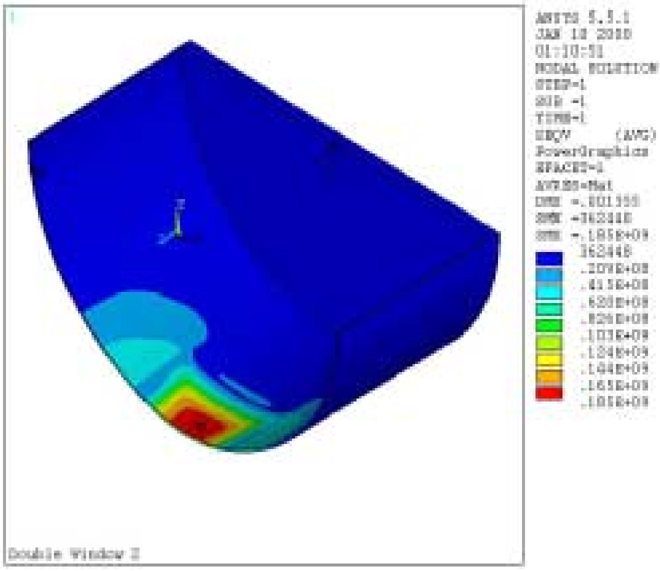
Beam current (mA)	2	10	20
Max. temp (°C)	571	1 497	2 657

Table 4. **Maximum temperature for the double window**

Beam current (mA)	2	10	20
Upper window (°C)	464	958	1576
Lower window (°C)	429	767	1187

After using FLUENT to produce a 3-D temperature distribution for the window, the result is transferred to ANSYS to calculate the thermal stress of the upper and lower window. Figure 7 shows the results of the ANSYS calculation. The maximum Von Mises thermal stresses are respectively about 185 and 97 MPa for the upper and lower beam window. In the stress calculation, the beam shape is assumed to be rectangular for the simplicity of calculation.

Figure 7. **Thermal stress distribution of the upper window for a 2 mA beam**



6. Conclusion

The thermal hydraulic and stress analysis of the liquid Pb-Bi target and beam window have been presented in this paper. Based on 2-D and 3-D analysis, temperature and velocity distributions were studied using FLUENT. We used ANSYS to calculate the stress of the beam window. A double window system was introduced to enhance the window cooling. The velocity of Pb-Bi flowing between two windows is set to be 6 m/s. When the beam current and velocity of up-coming Pb-Bi are 2 mA and 2 m/s respectively, the maximum temperature and thermal stress of the beam window were calculated to be 464°C and 185 MPa. Our target system is not a separate system, but a part of the whole sub-critical reactor. Therefore, the environment of the target should be considered to finalise the temperature and stress distribution. We are also considering the case of single window with a shape of hemisphere.

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