THE DESIGN OF A LEAD-BISMUTH TARGET SYSTEM WITH A DUAL INJECTION TUBE

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Abstract

A spallation target system is a key component to be developed for an accelerator driven system (ADS). It is known that a 15~25 MW spallation target is required for a practical 1000MWth ADS. The design of a 20 MW spallation target is very challenging because more than 60% of the beam power is deposited as heat in a small volume of the target system. In the present work, a numerical design study was performed to obtain the optimal design parameters for a 20 MW spallation target for a 1000 MW_{th} ADS. A dual injection tube was proposed for the reduction of the LBE flow rate at the target channel. The results of the present study show that a 30 cm wide proton beam with a uniform beam distribution should be adopted for the spallation target of a 20 MW power. When the dual LBE injection tube is employed, the LBE flow rate could be reduced by a factor of 4 without reducing the maximum allowable beam current.

Introduction

In an ADS, a high energy proton beam is impinged on a heavy metal target to produce spallation neutrons that are multiplied in a sub-critical blanket. Therefore, the spallation target is one of the most important units of an ADS.

The key issue in the target design is how to design an appropriate beam window and LBE flow so that the system can sustain thermal and mechanical loads as well as radiation damage. Recently there have been some intensive studies on the design of LBE spallation targets.[1][2] It is well known that a proton beam power of 15-25 MW is required for a practical size (about 1000 MWth power) of an ADS.[3] The design of a 20 MW spallation target is very challenging because more than 60% of the beam power is deposited as heat on the window and a small volume of the target system.

Due to the difficulties of designing high power targets, a three-beam target system was proposed by Forschungszentrum Karlsruhe and the target designs without beam windows are also considered in the MYRRHA project and the X-ADS design.[4, 5, 6] Although these proposals have some preferable characteristics for high power targets, they still have some difficulties in other aspects when compared to the more typical LBE target designs, i.e., a single beam with a solid window.

The main objective of the present paper is to show the possibility of designing a 20 MW LBE spallation target with a beam window. In a previous study, we designed a 20MW LBE target for HYPER.[7] However, it was found that the LBE flow rate was too high, almost 10% of the total coolant flow rate, and also the average LBE temperature rise in the target outlet was too low, compared to the LBE heat up in the core. These problems result in an increased pumping power of the coolant, potential thermal striping of the core upper structures, and a decrease of the thermal efficiency of the system. Thus, there is a big necessity to reduce the LBE flow rate in the target channel, without hampering the target performance.

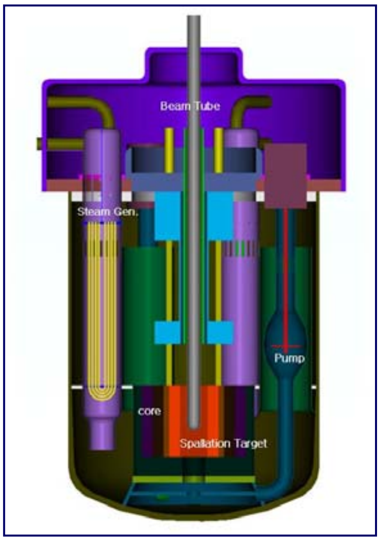
For this purpose, we introduce a dual LBE injection tube (DIT), which controls the LBE velocity distribution at the target inlet. Sensitivity studies for the DIT have been performed for the HYPER target system and the results are provided in this paper.

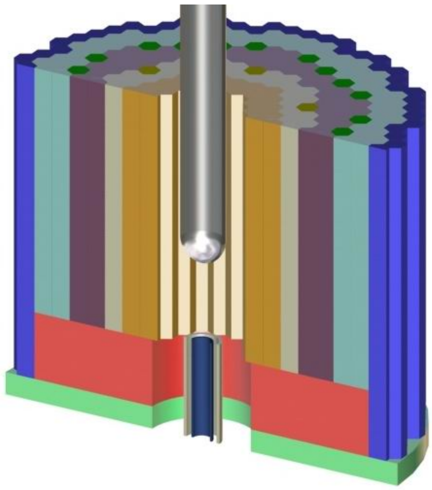
Target system

Korea Atomic Energy Research Institute (KAERI) has been developing an ADS called HYPER.[8] HYPER is a 1000MW$_{th}$ fast spectrum reactor with k_{eff}=0.98 and is designed to transmute the TRU, Tc-99 and I-129 coming from PWRs. HYPER is expected to need a maximum of a 19mA proton beam of 1GeV to sustain the 1000MW$_{th}$ power level. Figure 1 shows the conceptional layout of the HYPER and the target system schematically.

LBE is the target material and the target coolant. The beam window material is 9Cr-2WVTa. It is an advanced ferritic-martensitic steel that is known to be more resistant to LBE corrosion than austenitic steels and does not show a ductile-to-brittle transition temperature (DBTT) problem while being resistant to radiation damage [9].

Figure 1. **Conceptional layout of the HYPER and Target Systems**





(a) HYPER System (b) Target System

The material data for the calculation is listed in Table 1. The data used for the LBE and 9Cr-2WVTa are values at 450 °C and 500 °C, respectively. Since the data used for 9Cr-2WVTa is not available, the data of 9Cr-MoVNb except for the yield strength is used. Because those two steels are ferritic 9Cr steels, the thermal expansion coefficient, density, and thermal conductivity are not very different.

Table 1. **Material Data used for Calculations**

LBE (450°C)	Density (10.2 g/cm^3) Thermal conductivity (14.2 W/m·K) Thermal expansion coefficient (1.2×10^{-4} K^{-1}) Viscosity (1.39 Centipoise)	9Cr-2WVTa (500°C)	Density (7.6 g/cm^3) Thermal conductivity (30 W/m·K) Thermal expansion coefficient (1.23×10^{-5} K^{-1})

The cylindrical beam tube and hemi-spherical beam window are adopted in the basic target design of HYPER. Although hexagonal fuel assemblies surround the LBE flow channel, the target channel is assumed to have a cylindrical shape for the thermal-hydraulic calculation of the target channel. The beam window diameter (D_w) and the beam window thickness are 35 cm and 2.0 mm, respectively. The target channel diameter (D_t) is set at 66 cm. The beam diameter (D_b) should be as large as possible since a larger beam diameter means a smaller beam current density, which makes the peak temperature lower. There should be a minimum distance between the beam tube and the beam. But, since the proton beam may shift from its original axis, the minimum distance between the beam tube and the beam is 0.5cm bigger than a proton beam shift distance, that is, D_w - D_b = 5 cm. Two alternative radial distributions of the proton beam current density, that is, a uniform and a parabolic distribution, are considered in the thermal hydraulic analysis.

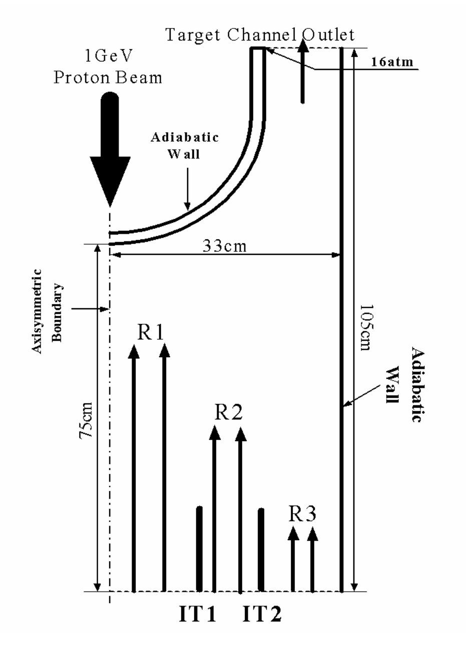
The LBE inlet temperature (T) is the same as the inlet temperature of the core coolant, 340°C. The pressure load, which is applied to the beam tube located 10 cm above the junction point of the beam tube and the beam window, is assumed to be 16atm. LBE inlet velocity (V) can be adjusted locally by using orifices although the flow is connected to the core coolant LBE.

The first criteria are the maximum allowable velocity and the temperature of the LBE. The erosion and corrosion rate of the structural material are increased as the LBE velocity and temperature increases. Therefore, the velocity of the LBE is fixed at 500°C and 2 m/s respectively.[10] The second set of criteria are the maximum allowable temperature and the stress of the beam window. Steels are usually degraded significantly if the temperature is too high. Therefore, 600°C is chosen as the maximum allowable temperature for the beam window. The stress intensity of the beam window is not allowed to exceed 1/3 of the yield strength of 9Cr-2WVTa [11]. The yield strength of 9Cr-2WVTa is 480MPa at 600°C, which means the maximum allowable stress is 160MPa.[12]

Numerical simulation

The heat generation inside the beam window and the LBE is calculated using the LCS 2.7(LAHET Code System). The thermal-hydraulic analyses of the target system are performed using the CFX 4.4 code. In the thermal hydraulic analyses, all the calculations were performed using the standard k-ε turbulence model to predict the turbulent flow characteristics, and the logarithmic law-of-the-wall to predict the near wall characteristics. Sufficient mesh refinement is used in each case to obtain y+ values between 30 and 200 in the heated regions, indicating that the turbulence model can provide reasonable predictions in these regions. The calculation is performed as a steady state simulation using the SIMPLEC solution algorithm and upwind differencing scheme. Also, the thermal hydraulic behaviours are evaluated using an axi-symmetric model. The maximal uniform inlet velocity of the LBE is decided based on the criterion that the LBE velocity at the target system does not exceed 2 m/s. Figure 2 shows the computational domain and the adopted boundary conditions schematically.

Figure 2. **The Computational Domain and the B.C.**



Heat Generation

The heat generation inside the beam window and LBE is calculated using the LCS 2.7 for the two types of proton beam distributions, that is, a uniform and a parabolic distribution. The results of the LCS are fitted to obtain the current density functions, which express the heat generation rates with a variable proton beam current.

1. A parabolic distribution is as follows:

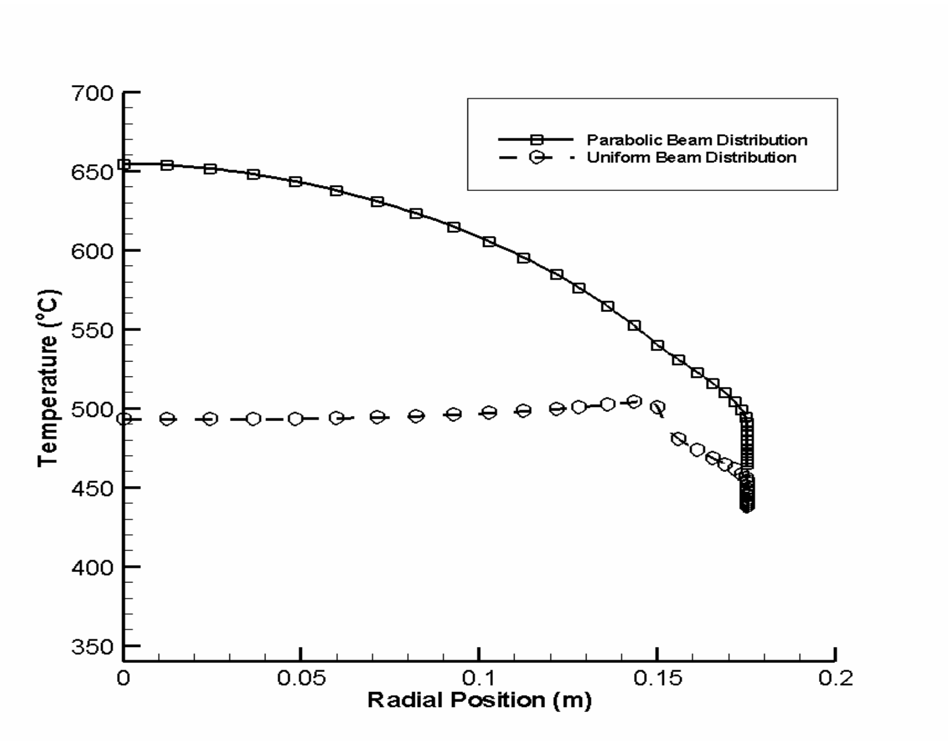
$$Q = C\frac{2I}{\pi R_b^4}(R_b^2 - \rho^2) \text{ , (unit: W/cm}^3\text{)} \qquad (1)$$

2. A uniform distribution is as follows:

$$Q = CI \text{ , (unit: W/cm}^3\text{)} \qquad (2)$$

where I=proton beam current (mA), R_b=beam radius (cm), ρ=distance from the center (cm), and C= fitted coefficient.

Figure 3. **Temperature distribution of the wetted surface at the beam window**



First, thermal hydraulic analyses of the reference target system are performed to compare the two beam profiles, uniform and parabolic, under the same calculation conditions and result is shown in Figure 3. The LBE inlet velocity is 1.31 m/s and the beam current is 20.0mA. The peak temperatures of the LBE with a parabolic and uniform beam distribution are 654°C, and 505°C, respectively. Also, the peak temperatures of the beam window with the parabolic and the uniform distribution are 736°C and 547°C, respectively. Clearly, the uniform beam distribution provides a lower peak temperature. In the same case, the allowable beam currents satisfying the design criteria with a parabolic and a uniform distribution are calculated to be 10.1mA, 19.3mA, respectively. All the cases show that the allowable beam current is constrained by the peak temperature of the LBE, 500°C, not by the peak temperature of the beam window, 600°C. In the case of the uniform beam distribution, the allowable beam currents are 19.3mA that is about twice of that of the parabolic beam profile case.

Consequently, the uniform beam target system has been adopted for HYPER. However, this target system has two unfavorable features, 1) the LBE flow rate (4562 kg/s) is almost 10% of that of the active core, 45506.26 kg/s, 2) the average LBE exit temperature (356°C) is too low when compared to the core average coolant temperature of 490°C. The large flow rate in the target channel increases the pumping power and the temperature difference between the target coolant and the core coolant may cause the so-called thermal striping behaviour. Thus, it is highly desirable that the LBE flow rate should be minimized, while keeping the maximum proton beam high.

For a comparison, we analysed the target with a 50% reduced LBE flow rate. In this case, the maximum beam currents satisfying the design criteria with the parabolic and the uniform distributions are calculated to be 5.4mA, 10.1mA, respectively. The target system with reduced flow rates does not offer a sufficient beam current to sustain the 1000MWth power level of the HYPER.

Effect of Single injection tube

Because the lesser the flow rate of the target channel is, the lesser the allowable beam current is, thus it is difficult for the present target system to reduce the flow rate with a sufficient beam current to sustain the 1000MWth power level of HYPER. Therefore, to reduce the flow rate at the target system, a cylindrical injection tube (IT), which is located in the centre of a target channel, is introduced.

In order to investigate the effect of the single injection tube (SIT), thermal hydraulic analyses are performed with the two types of proton beam distributions with a beam current of 20mA. The SIT diameter and the SIT height are 31 cm and 10 cm, respectively, and the thickness of the IT is 2mm. Because the proton beam diameter is 30 cm, the SIT diameter is wider than that of the proton beam to avoid any direct irradiation of the proton beam at the SIT. The LBE inlet velocity at the target channel without SIT is 0.655 m/s. The LBE inlet velocities of R1 and R2 (+R3) are 1.5 m/s and 0.417m/s, respectively.

Figure 4. **The temperature distributions of the wetted surface at the beam window**

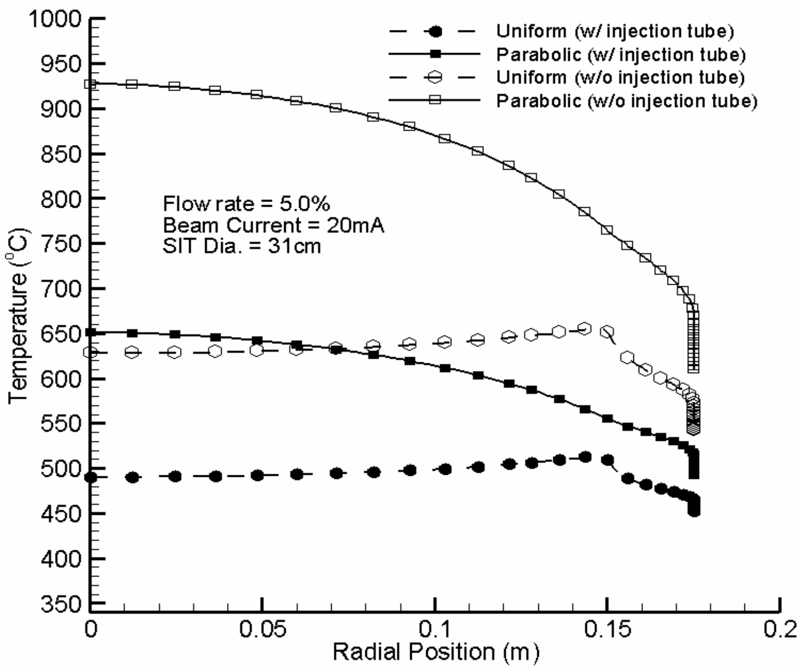
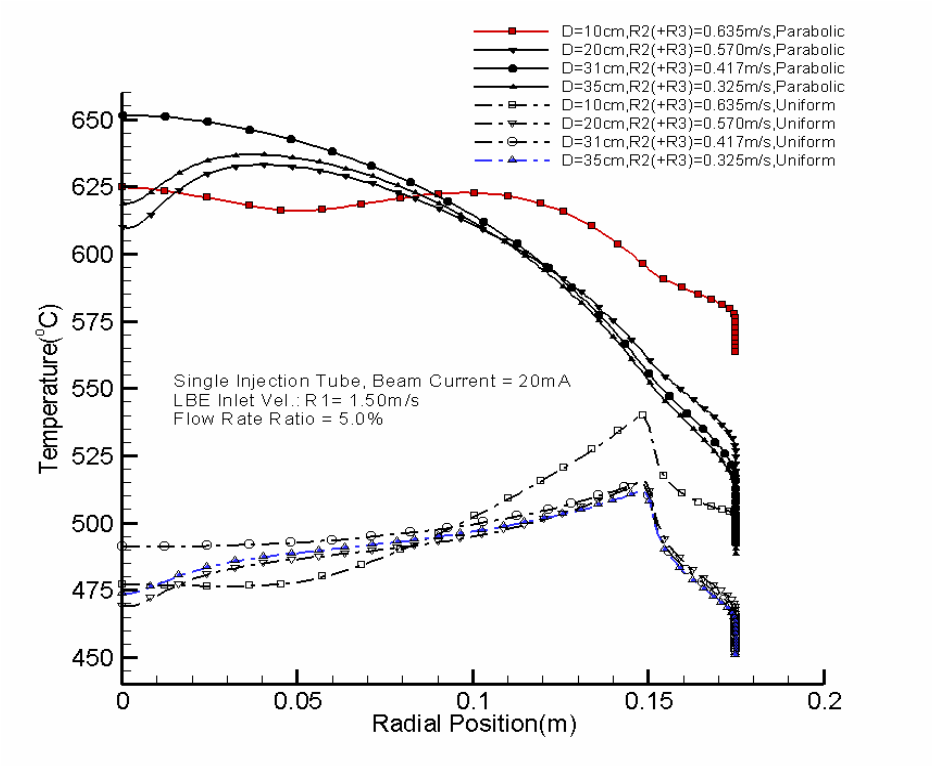


Figure 4 shows the temperature distributions of the wetted surface at the beam window with or without the SIT. Without the SIT, the peak temperature of the wetted surface at the beam window is 928°C for the parabolic beam and 657°C for the uniform beam. With the SIT (diameter = 31cm), the peak temperature of the wetted surface at the beam window is 652°C with the parabolic beam and 515°C with the uniform beam. With the SIT, the peak temperature of the wetted surface at the beam window is significantly reduced.

For the SIT concept, thermal hydraulic analyses were performed to determine the maximum beam current satisfying the design criteria. The LBE inlet velocities of R1 and R2 (+R3) are 1.635 m/s and 0.378 m/s, respectively. The maximum beam currents satisfying the design criteria with the parabolic and the uniform beam distributions are calculated to be 10.3mA, 19.6mA, respectively. The results show that the introduction of an SIT is a good counterproposal to reduce the flow rate of the target system with a sufficient beam current to sustain the 1000MWth power level of the ADS.

In order to investigate the effect of a variation of the SIT diameter, thermal hydraulic analyses are performed. The diameter of the SIT is varied from 10 cm to 35 cm, and the SIT height is fixed at 10 cm. The LBE inlet velocity of R1 is fixed at 1.5 m/s and the LBE inlet velocity of R2(+R3) is decided based on the criterion that the flow rate of the target system does not exceed 5.0% of that of the active core. The proton beam current is 20mA. Figure 5 shows the temperature distributions of the wetted surface at the beam window with the SIT diameter variation. In the case of the uniform beam, the wider the diameter of the SIT is, the greater the cooling effect at the beam window is. In the case of the parabolic beam, the narrower the diameter of the SIT is, the greater the cooling effect at the beam window is.

Figure 5. **The temperature distributions of the wetted surface at the beam window with the SIT diameter variation**

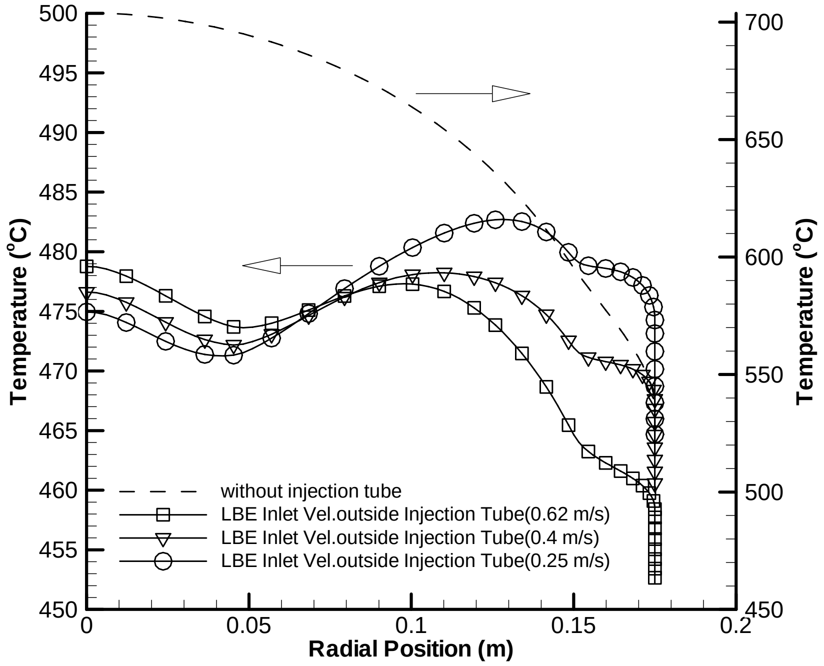


In order to investigate the changes of the temperature and the velocity distribution in the target system with the flow rate variations, thermal hydraulic analyses are performed. The SIT diameter and height are fixed at 10 cm. The beam currents of the parabolic and uniform beams are 12.3mA and 19.6mA, respectively. While the LBE inlet velocity of R1 is fixed at 1.95 m/s, the flow rate of R2 (+R3) is reduced little by little. The flow rate of R1 is 156 kg/s, that is, 0.34% of that of the active core.

The temperature distributions of the wetted surface at the beam window are shown in Figure 6. According to the flow rate reduction, in the case of the parabolic beam, the peak temperature of the wetted surface at the beam window gradually shifts outwards from the centre of the beam window along the beam window surface, which is contrary to the typical temperature distribution at the beam window surface with a parabolic beam. In the case of the uniform beam, the peak temperature of the beam window occurs near the intersection of the proton beam boundary with the beam window and is increased with the flow rate reductions.

Figure 6. **The temperature distribution of the wetted surface at the beam window with the flow rate reduction**

(a) Parabolic beam



(b) Uniform beam

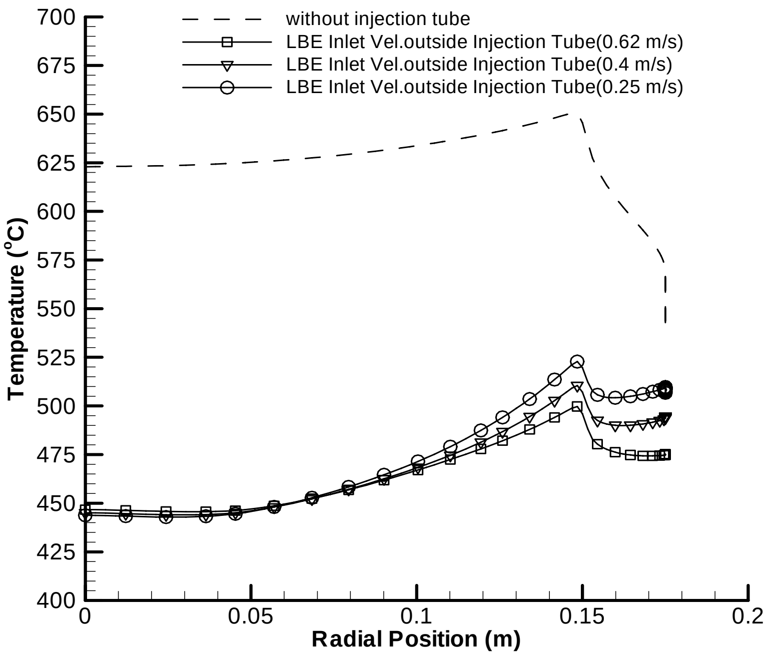


Figure 7. **The velocity and temperature distribution in the target channel with the flow rate variations**

(a) Velocity (b) Temperature (uniform)

w/o IT 0.62 m/s 0.25 m/s w/o IT 0.62 m/s 0.25 m/s

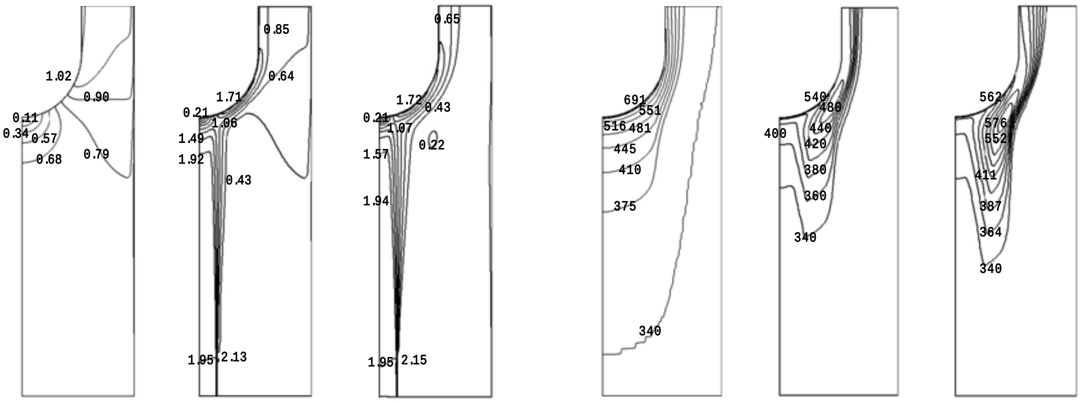


Figure 7 shows the velocity and the temperature distribution in the target system with the flow rate reduction of R2 (+R3). Due to the relatively high velocity of the LBE of R1, the flow stagnation region existing below the beam window center is substantially decreased. But, with the injection tube, another flow stagnation region developed below 45 degrees from the beam window center when the flow rate of R2 (+R3) is reduced substantially. It causes a temperature increase of the LBE near the intersection of the proton beam boundary with the beam window and the peak temperature of the LBE occurs at the thermal island in the flow field of the LBE.

Effect of dual injection tube

It is clear that the target system with an SIT offers not only a more allowable beam current but also a significantly reduced flow rate at the target channel. But, when a SIT is employed, a new flow stagnation region develops below the beam window with the flow rate reductions. It causes a temperature increase of the LBE near the intersection of the proton beam boundary with the beam window. Also, with the SIT concept, the LBE flow rate could not be further reduced without reducing the maximum allowable beam current. Therefore, we introduced a dual injection tube (DIT), which provides a greater degree of freedom in the LBE flow field control.

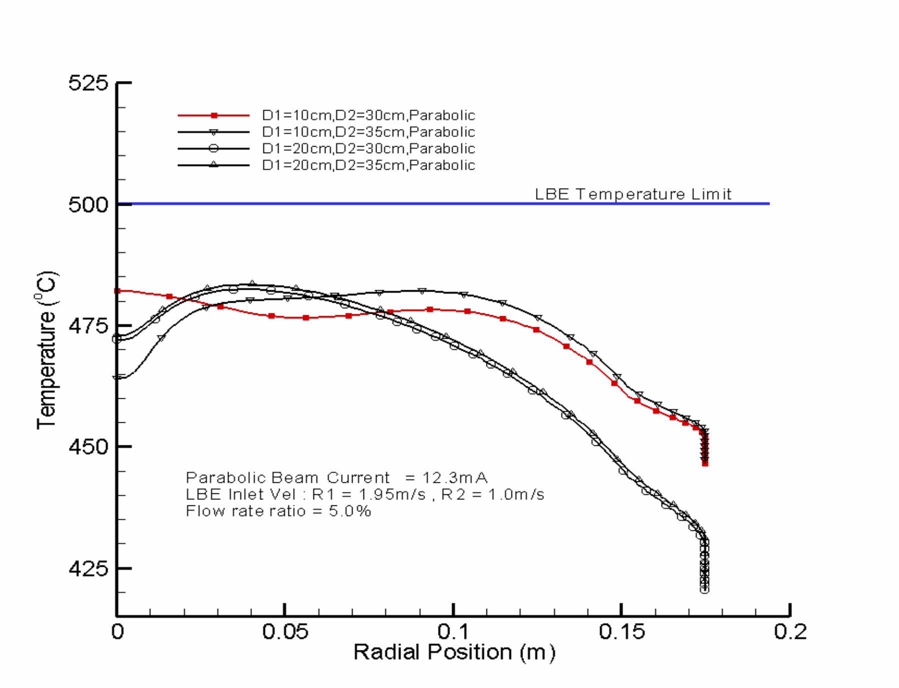
In order to investigate the effect of DIT, thermal hydraulic analyses are performed with a fixed flow rate of the target system, 5% of that of the active core, and the results are shown in Figure 8. There are 4 kinds of DIT and Table 2 shows them. The LBE inlet velocities of R1 and R2 are 1.95m/s and 1.0m/s, respectively. The beam currents of the parabolic beam and the uniform beam are 12.3mA and 19.6mA, respectively.

Table 2. **Parameter sets of DIT**

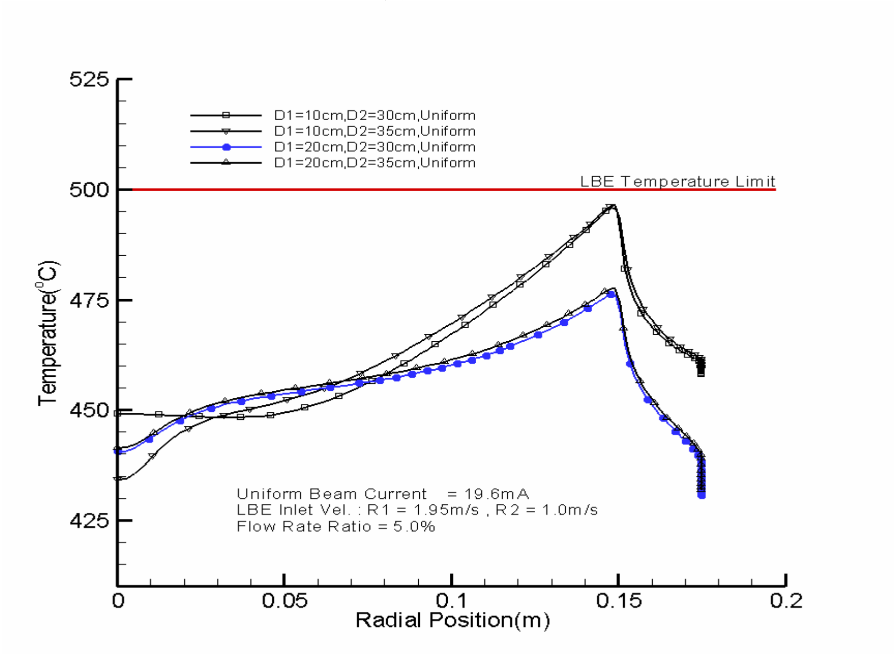
Case 1	Case 2	Case 3	Case 4
D1=10cm, D2=30cm	D1=10cm, D2=35cm	D1=20cm, D2=30cm	D1=20cm, D2=35cm

Figure 8. **The temperature distributions of the wetted surface at the beam window with DIT diameter variations**

(a) Parabolic



(b) Uniform

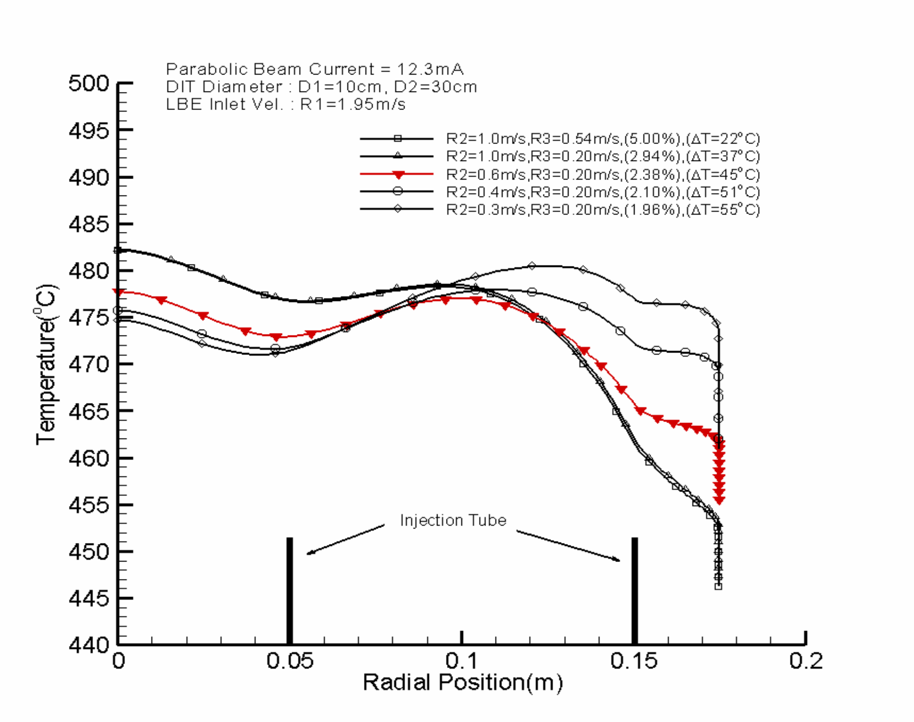


In Figure 9, in the all cases except for Case 1, a drop in temperature occurs at the beam window centre. In the case of the uniform beam, the wider the diameter of the inner IT (IT1) is, the greater the cooling effect at the beam window is. In the case of the parabolic beam, the smaller the diameter of the IT1 is, the greater the cooling effect at the beam window is. The results show that Case 1 with the parabolic beam and Case 3 with the uniform beam would be the optimum parameter set from the viewpoint of the peak temperature at the beam window.

In order to investigate the changes of the temperature distribution at the beam window with the flow rate variations, thermal hydraulic analyses are performed with Case 1 and Case 3 and the results are shown in Figures 9 and 10. The beam currents of the parabolic and the uniform beam profile are 12.3mA and 19.6mA, respectively. The LBE inlet velocities of R1 of Case 1 and Case 3 are 1.95 m/s and 1.80m/s, respectively. While the LBE inlet velocity of R3 is fixed at 0.2m/s, the flow rate of R2 is reduced little by little.

Figure 8. **The temperature distributions of the wetted surface at the beam window with the parabolic beam**

(a) Case 1



(b) Case 3

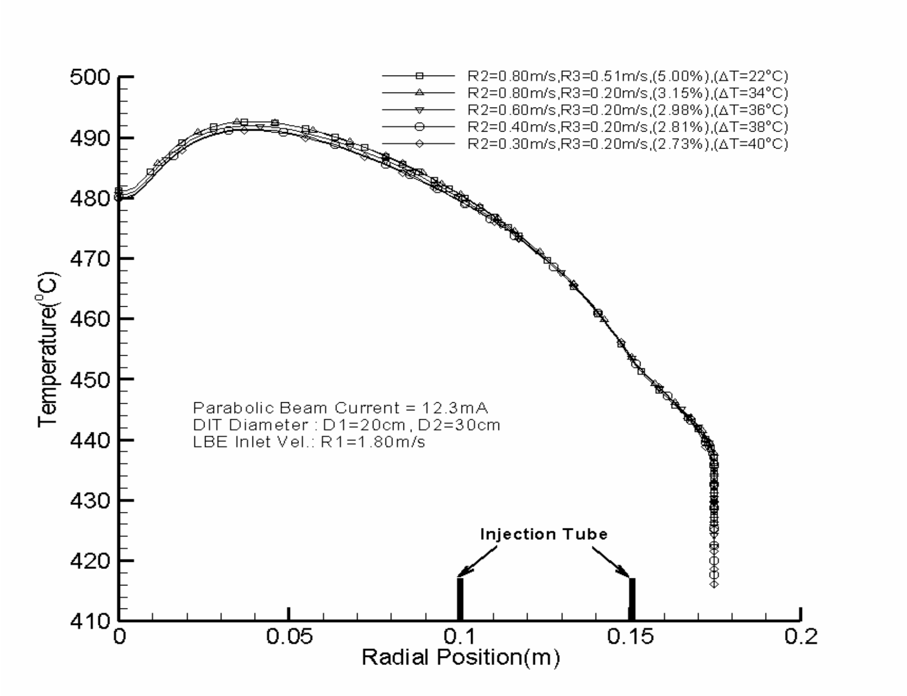
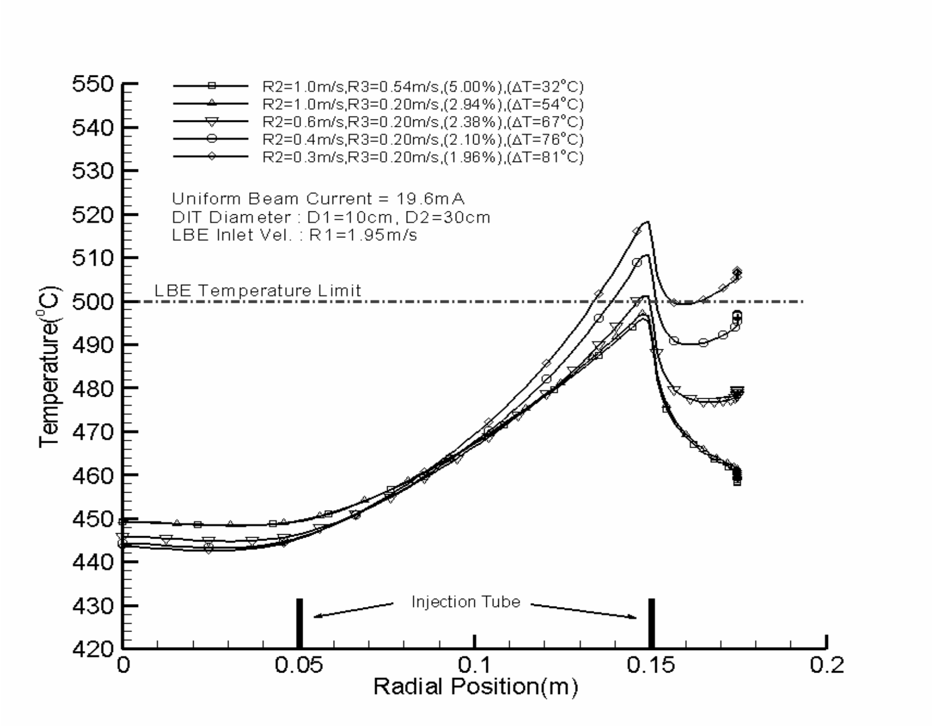
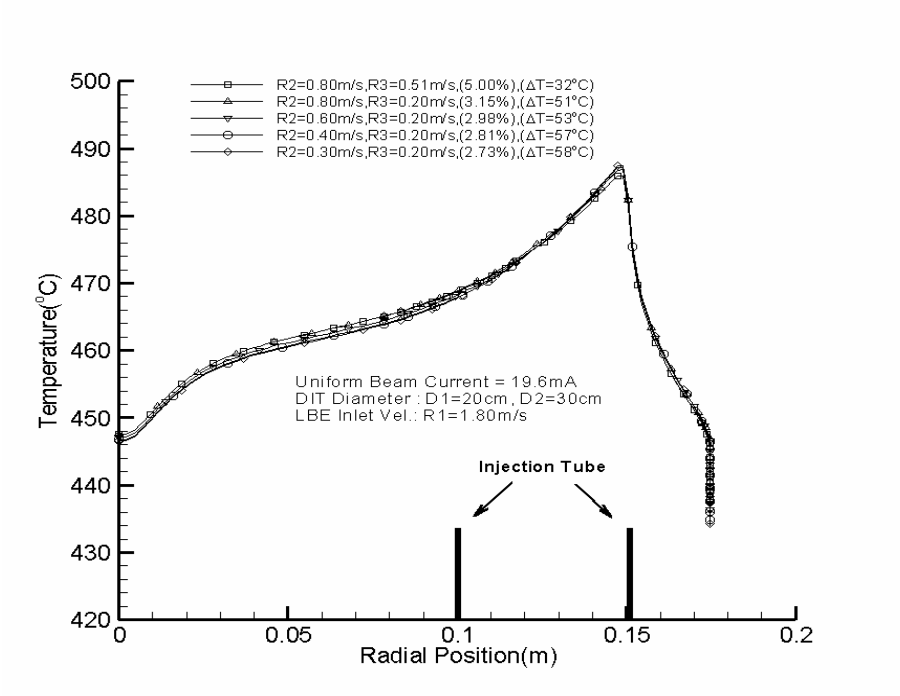


Figure 10. **The temperature distributions of the wetted surface at the beam window with the uniform beam**

(a) Case 1



(b) Case 3

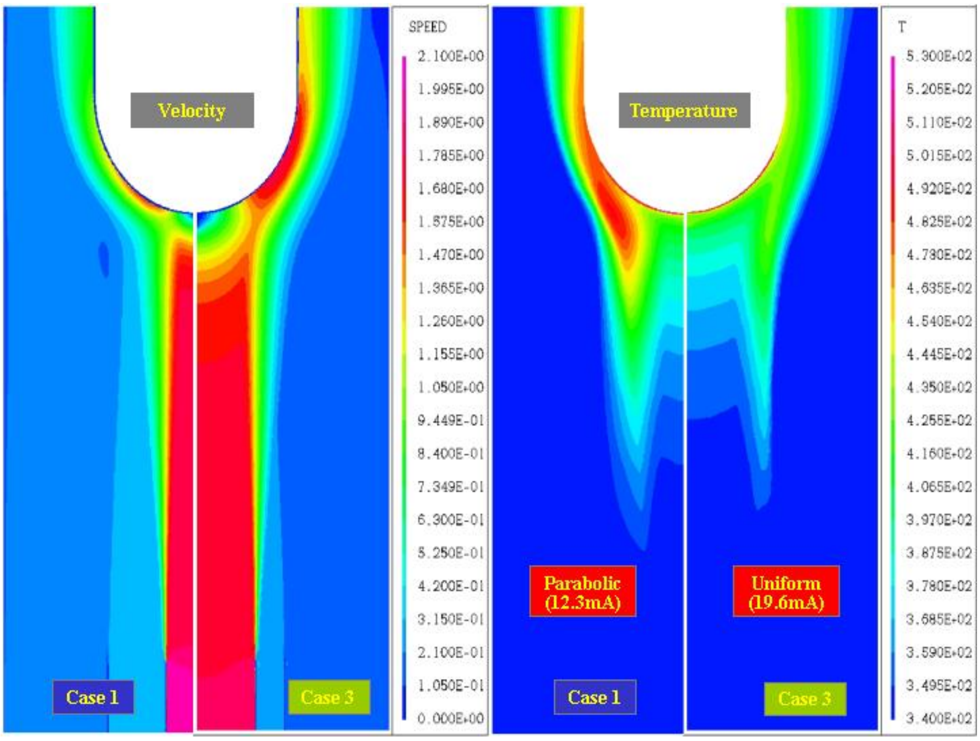


In Figure 9, Case 1 is more effective for the beam window cooling than that of Case 3. In the case of R2 = 0.3m/s, the LBE flow rate of the target channel could be reduced by a factor of 5 with an increased allowable maximum beam current, that is, 14.0mA and average LBE exit temperature, that is, 395 °C. In the case of R2 = 0.6m/s which would be the optimum case from the viewpoint of the peak temperature at the beam window, the allowable maximum beam current is 14.28mA.

As shown in Figure 10, Case 3 is more effective for the beam window cooling than that of Case 1. Also, the temperature rises of the wetted surface at the beam window with the flow rate reductions are smaller than that of Case 1 or the SIT. The results show that a new flow stagnation region developed below the beam window is controlled very well by the DIT. In the case of R2 = 0.3m/s, the LBE flow rate of the target channel could be reduced by a factor of 4 with an increased allowable maximum beam current of 21.27mA and an average LBE exit temperature of 398 °C.

The temperature and the velocity distribution in the target channel with Case 1 and Case 3 are shown in Figure 11. In case of the Case 3, we can not see another flow stagnation region developed beneath forty five degrees from the beam window centre and thermal island in the flow field of the LBE.

Figure 11. **The temperature and the velocity distribution at the target system**



Conclusions

In this paper, to reduce the flow rate at the target system, a cylindrical injection tube, which is located in the centre of a target channel, is introduced.

With a dual injection tube of a 10cm inner tube diameter and a 30cm outer tube diameter, the allowable maximum beam current is 14.0mA for a parabolic beam that is about 159% higher than that of the target system without an injection tube. Also, with a dual injection tube of a 20cm inner tube diameter and a 30cm outer tube diameter, the allowable maximum beam current is 21.27mA for a uniform beam that is about 111% higher than that of the target system without an injection tube. From the viewpoint of the thermal hydraulics, the results show that a smaller diameter of the inner injection tube would be appropriate for the parabolic beam and a wider diameter of the inner injection tube would be appropriate for the uniform beam.

The results show that the target system with a dual injection tube offers not only a higher allowable beam current but also a significantly reduced flow rate at the target channel. If the inlet velocity of R3 is further reduced, the LBE flow rate could be decreased without reducing the maximum allowable beam current and to achieve this a related study is underway.

Acknowledgments

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