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Thermal hydraulic studies of spallation target for one-way coupled Indian accelerator driven systems with low energy proton beam

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Abstract. BARC has recently proposed a one-way coupled ADS reactor. This reactor requires typically ∼1 GeV proton beam with 2 mA of current. Approximately 8 kW of heat is deposited in the window of the target. Circulating liquid metal target (lead/lead–bismuth–eutectic) has to extract this heat and this is a critical R&D problem to be solved. At present there are very few accelerators, which can give few mA and high-energy proton beam. However, accelerators with low energy and hundreds of micro-ampere current are commercially available. In view of this, it is proposed in this paper to simulate beam window heating of ∼8 kW in the target with low-energy proton beam. Detailed thermal analysis in the spallation and window region has been carried out to study the capability of heat extraction by circulating LBE for a typical target loop with a proton beam of 30 MeV energy and current of 0.267 mA. The heat deposition study is carried out using FLUKA code and flow analysis by CFD code. The detailed analysis of this work is presented in this paper.

Keywords. Accelerator driven systems (ADS); lead–bismuth–eutectic (LBE); neutron spallation target; FLUKA; CFD; window.

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1. Introduction

Recently, studies have been taken up in world's leading nuclear research institutes to develop accelerator driven systems (ADS) [1]. The ADS system utilizes neutrons produced in a spallation target by a high-energy proton beam to drive a blanket assembly containing both fissionable fuel and radioactive waste. The spallation target is ideally conceived to be a high atomic mass material and heavy density liquid metals like lead and LBE fit the requirement extremely well [2,3]. The novel feature of ADS is the presence of a neutron spallation target in the core of the reactor, which always operates under sub-critical conditions. A proton beam (energy: ∼1 GeV and current: few to tens of mA) interacts with the target, which is located in the core and produces spallation neutrons that diffuse into the reactor and drive

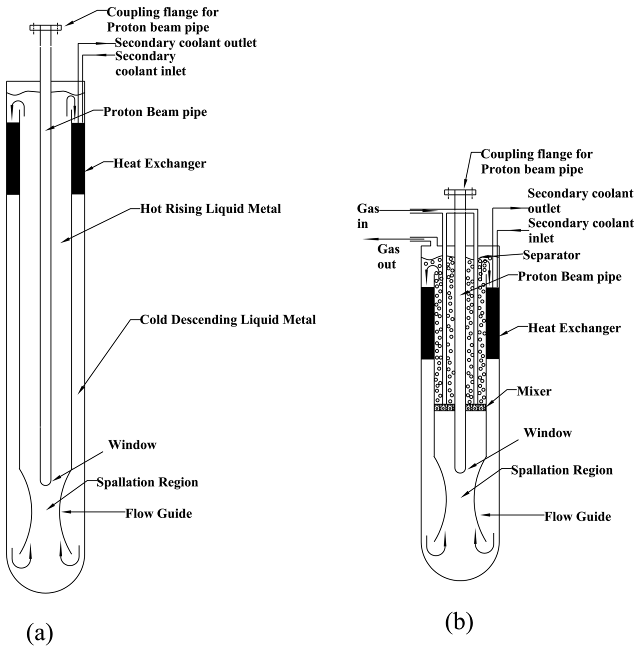

Figure 1. (**a**) Buoyancy- and (**b**) gas-driven window target module.

the reactor. One of the critical operating conditions for the ADS spallation target is: high volumetric heat deposition in the window (solid barrier that isolates the beam transport pipe and the liquid LBE) of the target module. Typically ∼4 kW/mA of heat is deposited in the window in a small volume [4]. In addition, large amount of heat is deposited in the target (for a GeV beam, ∼65% of beam energy is deposited in the target). Various methods for circulating the liquid metal have been proposed which are pump-driven, buoyancy-driven and gas-driven [5,6]. In the buoyancy-driven module (figure 1a), circulation of liquid metal target is induced by buoyancy force. The heat deposition by the proton beam raises the LBE temperature in the hot leg, while the cold leg is maintained at low temperature through the secondary coolant flow in the heat exchanger. The higher the temperature difference, greater will be the LBE flow rate. However, due to the corrosion effects of LBE [7], an upper limit of temperature difference (∼150°C) has to be maintained. In the gas-driven system (figure 1b), the effects of natural circulation are enhanced by injecting gas, which increases available pressure head to circulate the liquid metal. However, the spallation and window regions are the same for both these configurations.

2. One-way coupled Indian ADS

One-way coupled booster reactor system is the reactor concepts in which our institution is presently working [8]. The main advantage of these systems is the

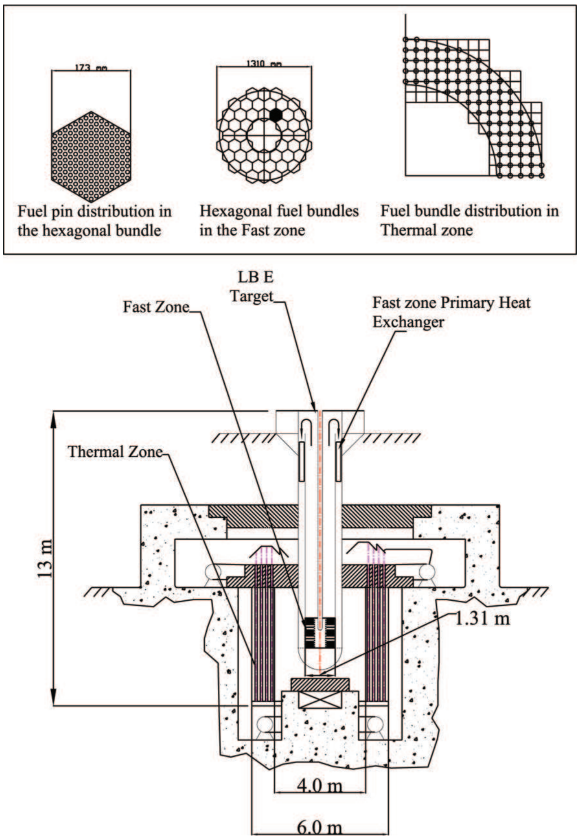

Figure 2. Schematic of 750 MW (thermal) one-way coupled ADS.

requirement of lower beam currents. The proposed one-way coupled booster reactor system can be operated for low proton beam currents of 1–2 mA (1 GeV energy) for the power output of 750 MW_{th}. The basic idea of the booster system is to have a fast booster reactor zone of low power ($\sim$100 MW_{th}), which is separated by a large gap from the main thermal reactor zone. In this arrangement, the spallation neutron source feeds neutrons to the fast reactor zone, where neutrons are further multiplied. Further in this system, the neutrons from the booster region enter the main reactor but very few neutrons from main reactor return to booster, thus ensuring one-way coupling. In this work, several possible configurations of the booster and thermal regions were presented.

The preliminary design of this hybrid ADS reactor consists of fast and thermal reactor zones producing about 100 MW_{th} and 650 MW_{th} respectively. The schematic of the system is shown in figure 2. The fast core consists of 48 hexagonal fuel bundles each containing 169 fuel pins of 8.2 mm diameter arranged in 11.4 mm triangular array pitch. The average thermal power per fuel pin is $\sim$13.46 kW. However, due to neutron flux peaking effect, the maximum fuel pin power can be up to 2.5 times this average power. The thermal reactor consists of heavy water as moderator and coolant similar to a typical CANDU-type Indian PHWR except for fuel composition. Though the gap between fast and thermal zones essentially provides one-way coupling of neutron flux, a thermal neutron absorber at the fast zone boundary is also contemplated to ensure one-way coupling. Also, LBE has been chosen as one of the coolants for fast core. The overall target module dimensions and flow rates have already been estimated [5,6,9].

One of the critical R&D problems to be solved is the extraction of window heat by circulating liquid metal target (lead/lead–bismuth–eutectic). In addition to theoretical studies, it will be useful to actually simulate these heat loads to directly test the target capability. At present, there are very few accelerators, which can give high-energy proton beam (hundreds of MeV) with few milli-Ampere of current. Fortunately, accelerators of low energy (tens of MeV) are commercially available which can give hundreds of micro-Ampere currents. These accelerators can be conveniently used for window heat simulation. Low-energy accelerators have been proposed to simulate issues like detection, trapping with suitable filters, safe storage etc. of polonium-210 produced [10]. However, we are proposing the low-energy accelerators for thermal-hydraulic simulation studies.

In this paper, a typical proton beam of 30 MeV and 0.267 mA beam current has been proposed for the window heat simulation. The penetration of the beam in the proposed target material (T91 steel) is around 1.8 mm and most of the heat is deposited within the window. Thus, this beam simulates the heat load of 1 GeV proton beam of $\sim$2 mA current. Unlike actual target loop, we cannot have buoyancy-driven target loop since the heat deposited by the low-energy beam is very small (tens of kW as compared to few MW). We have to opt for gas-driven loop only (we can have pump-driven circulation also). Detailed heat deposition by proton beam having parabolic current density distribution with beam radius of 55 mm has been calculated using FLUKA code for the LBE target geometry with specific material of construction. These data are fed into a two-dimensional finite element method (FEM) based CFD code, to determine the temperature distribution for different flow rates in the window region. The details of this analysis are presented in this paper.

3. Target geometry and material of construction

3.1 *Design of target loop*

The target loop for window heat simulation has been designed by using one-dimensional codes [5]. The current density of the beam is taken as parabolic with 55 mm radius. The beam current essentially decides the proton beam pipe diameter, which is taken as 0.1282 m ID and 0.1342 m OD. The details of other components are summarized in figure 3. It is further assumed that the outer riser pipe is thermally insulated by a suitable material. Three flow rates have been chosen with inlet temperature as 200°C (based on the heat exchanger design). The window that separates the vacuum in the beam pipe from the coolant is a hemisphere from outside of 0.0671 m of radius and an ellipsoid from inside with semi-minor and semi-major axes 0.0641 m and 0.0656 m respectively. This configuration provides a

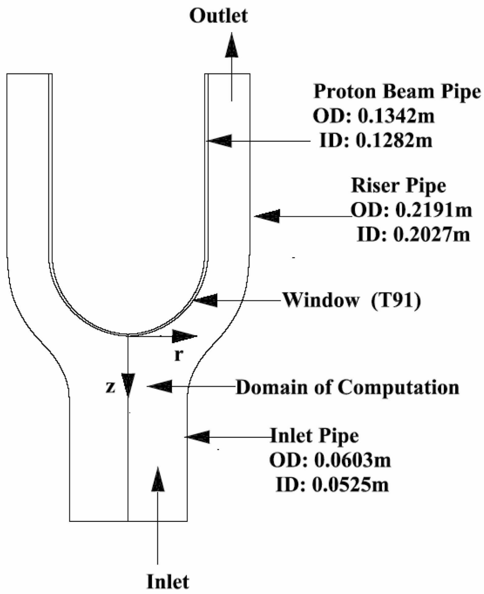

Figure 3. Schematic of the computational domain.

variable window thickness ranging from 1.5 mm at the beam axis to 3.0 mm at the junction of the beam pipe. This is done in order to reduce the thickness as much as possible in the zone where the heat density is higher, keeping the structural integrity intact. T91 steel has been chosen as window material and T91/SS-316 as materials of construction for other components [11].

3.2 *Heat deposition calculations by FLUKA code*

The conversion of beam energy into heat inside the target module due to interaction of 1 GeV proton has been estimated using FLUKA Monte Carlo code, which is a general-purpose tool for the calculations of particle transport and interactions with matter, with recent developments [12, 13]. The heat deposition is a function of density and atomic number of the material with which the proton interacts and is therefore different for window and coolant materials. The heat loss at a given energy is the sum of two components; the contributions coming from the ionization process and hadronic interactions. At low energy, as the hadronic contribution is not very significant, the total heat loss is primarily Coulombic in nature. The $\mathrm{d}E/\mathrm{d}z$ energy loss as a function of z has a range r_b followed by a Bragg peak, an interaction process that can be described well by the Bethe formula. Since the beam window is exposed to the highest temperature, it is important to study heat loss in the window very carefully, to optimize flow and geometry parameters for effective cooling of the beam window.

4. Thermal-hydraulic analysis

4.1 *Governing equations*

The governing equations are simplified by the following assumptions: (i) geometry is limited to two dimensions, (ii) computational model is having z-axis symmetry and (iii) flow is assumed turbulent, incompressible except for density variation due to temperature, i.e. Boussinesq approximation for buoyancy effects. The volumetric heat deposition is supplied by proton beam as calculated by FLUKA code. The heat generated inside the window diffuses out of the window and consequently is carried away by LBE by mixed convection. Therefore, in order to arrive at the window temperature profile, a conjugate heat transfer problem has been solved. Based on these assumptions, the continuity, momentum, energy, k and ε equations are taken in dimensional form.

4.2 *Numerical scheme*

The numerical investigations were accomplished using a finite element method based on streamline upwind Petro-Galerkin (SUPG) technique and following the Eulerian velocity correction approach [14]. Time-dependent governing equations for the conservation of mass, momentum and energy in the fluid are solved. For conjugate analysis, the conduction equation in the solid is solved. Structured grid has been generated using partial differential equation technique (Laplace equation). Higher grid refinement was ensured for the fluid zone near the window, which is the region of interest.

4.3 *Flow analysis*

The analysis is carried out for 30 MeV proton beam of 0.267 mA current and three flow rates i.e. 15 kg/s, 30 kg/s and 50 kg/s. The liquid metal coolant, after rejecting heat in the heat exchanger, enters the flow guide at the bottom and rises upward in the flow guide. The liquid metal extracts heat from the window and flows into the annular riser pipe where the gas is injected for the purpose of circulation and returns to the top of the target module. Since detailed temperature distribution is required only in the window and spallation region, the detailed analysis has been carried out in the selected regions only (inlet region, window region, circular to annular flow transition region and bottom portion of riser pipe) as shown in figure 3. Velocity components are specified at the inlets along with temperature, which has been taken as 473 K. Wall boundary conditions have been implemented for the flow guide, external target wall, riser pipe and the proton pipe including window. Symmetry condition has been invoked and analysis carried out for one half of the physical domain to save computational time. The heat source distribution computed by the FLUKA code is used as input data. In this conjugate heat transfer problem, the continuities of temperature as well as heat flux at the liquid metal and

Table 1. Window and target temperatures for various flow configurations (beam energy and current: 30 MeV and 0.267 mA; window thermal load: 8.0 kW, total heat deposited by beam: 8.0 kW; $T_{\text{LBE-inlet}} = 473$ K with window with variable thickness, i.e. 1.5 mm at the center and 3 mm at the outer rim).

No.	Radius of annular transition region	LBE flow rate (kg/s)	$T_{\text{LBE-Outlet}}$ (K)	$T_{\text{window max}}$ (K)	$T_{\text{LBE max}}$ (K)
1	28.0 mm	15	476	681	617
2		30	475	648	581
	(C1)	50	474	627	560
4	13.8 mm	15	477	623	564
5		30	475	593	535
6	(C2)	50	474	588	521

the window interface are satisfied. Wall function approach for low Prandtl number fluids has been implemented.

5. Results and analysis

As mentioned earlier, analysis has been carried out for different flow rates and one current for two typical geometries. The geometric configurations vary in terms of annular cross-section in the transition annular region near the spallation zone. The transitional annular radius in geometric configuration C1 is 28.0 mm (see table 1) and C2 is 13.8 mm respectively. The detailed temperature and velocity distribution in the window region for C2 configuration are presented in figures 4 and 5 respectively corresponding to the flow rate of 30 kg/s. The summary of the results is shown in table 1 for all flow conditions. We see that, C2 configuration cools the window better due to higher velocity in the transition region. As expected, increase in the flow rate cools the window better. We see that even 15 kg/s flow rate cools the window within acceptable range. It may be noted that in actual target with 1 GeV beam, large additional heat is deposited in the spallation region of the target, thus necessitating higher flow rates.

6. Summary and conclusions

BARC has recently proposed a one-way coupled ADS reactor. This reactor requires typically ∼1 GeV proton beam with 2 mA of current. Approximately 8 kW of heat is deposited in the window of the target. Circulating liquid metal target (lead/lead–bismuth–eutectic) has to extract this heat and this is a critical R&D problem to be solved. At present there are very few accelerators, which can give few mA and high-energy proton beam. However, low energy and hundreds of micro-Ampere current accelerators are commercially available. In view of this, it is proposed to simulate beam window heating with low-energy proton beam. Preliminary thermal

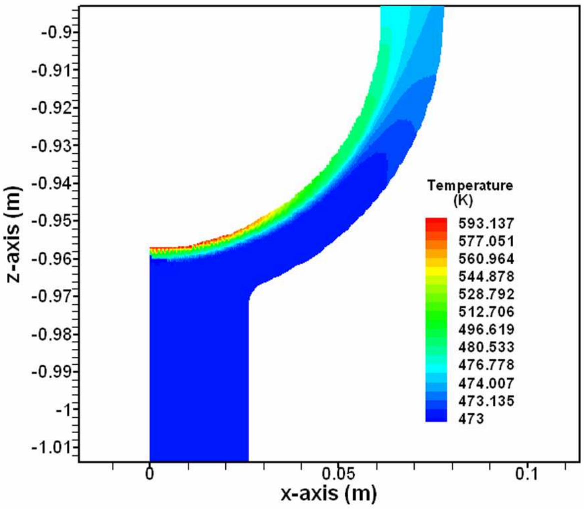

Figure 4. Temperature contours for 30 kg/s flow rate in geometry with smaller transitional annular radius (13.8 mm) for a proton beam of 30 MeV energy and 0.267 mA beam current.

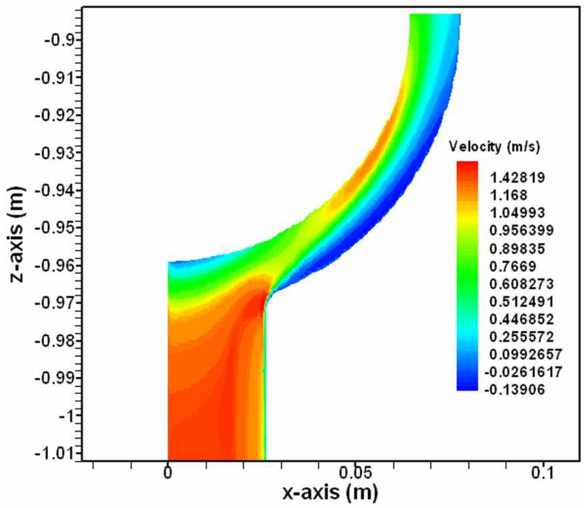

Figure 5. Velocity contours for 30 kg/s flow rate in geometry with smaller transitional annular radius (13.8 mm) for a proton beam of 30 MeV energy and 0.267 mA beam current.

analysis of a spallation target and window region has been carried out to study the capability of heat extraction by circulating LBE for a typical target loop with a proton beam of 30 MeV energy and current of 0.267 mA. The heat deposition is carried out using FLUKA code and flow analysis by CFD code for two typical geometries. The assumed flow rates of liquid metal are able to cool the window within the acceptable temperature range. Ideally, experiments should be carried out in a low-energy accelerator to validate the prediction. These experiments can play a key role in developing suitable targets for ADS. Future work will be carried out to further improve the window cooling by optimizing the flow configuration near the window. In addition, thermo-mechanical analysis will be carried out.

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