DESIGN OF A LBE SPALLATION TARGET FOR FAST-THERMAL ACCELERATOR-DRIVEN SUB-CRITICAL SYSTEM (ADS)

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Abstract

Preliminary design of the Indian 750 MW_{th} fast-thermal ADS indicated that a fairly large thermal power was possible with a proton beam of 1 GeV and current in the range 2-3 mA. In this paper, preliminary thermal-hydraulic studies carried out on the spallation target of window type ADS based on LBE, with a thermal power of 100 MW in the fast zone, are presented. The studies have been carried out both for buoyancy as well as gas driven target systems and complete analysis of the loop consisting of spallation region, riser, two-phase flow region of the riser (for gas-driven target) heat exchanger, downcomer etc has been done. The model is based on one-dimensional single and two-phase flow. Parametric analysis for different flow rates, beam currents (2 and 3 mA and 1 GeV), geometry etc is presented and comparison made between buoyancy and gas-driven systems.

Introduction

Accelerator-driven Sub-critical Systems (ADS) have evoked considerable interest in recent years. [1] In earlier publications [2,3], the BARC group proposed a one-way coupled booster reactor system, which could be operated at proton beam currents as low as 1-3 mA for a power output of 750 MW_{th}. Here, the basic idea is to have a fast booster reactor zone of low power (~ 100 MW_{th}), which is separated, by a large gap from the main thermal reactor of 650 MW_{th}. In this preliminary design, 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 about 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 or alternatively AHWR.

In order to develop ADS system as a long-term programme, basic R&D programme has been initiated to study spallation target. For this purpose, the process of development of CFD codes and setting up of experimental target loops for simulation of thermal-hydraulics and diagnostics have already been initiated. In this paper preliminary thermal-hydraulic studies carried out for molten circulating LBE target for the beam currents in the range of 2-3 mA and energy of 1 GeV have been presented.

Selection of target loop

For our programme, we have chosen molten LBE as target with separated loop. Presently we are considering both window as well as windowless configurations. For window configuration, both buoyancy and gas driven circulation have been considered (Figure 1). [4] In this paper, studies carried out for window configuration are presented.

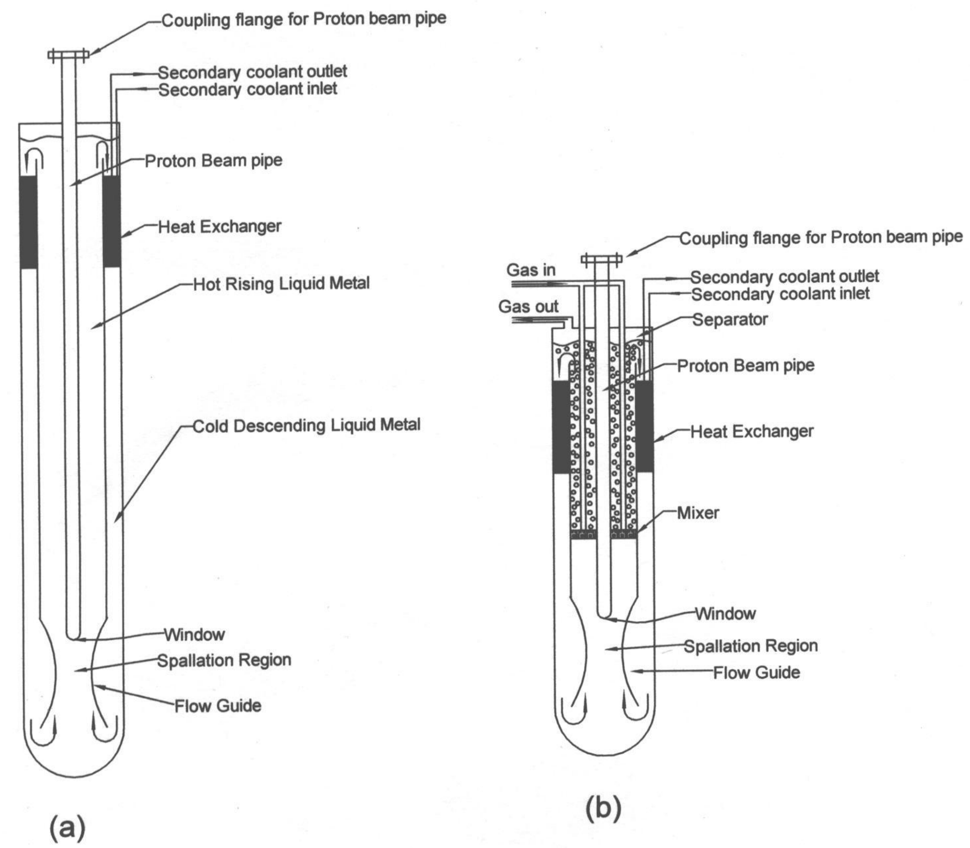
Flow under natural convection (buoyancy driven flow)

In this design (Figure 1a), flow of liquid metal of spallation target is induced by buoyancy force. A large value for volumetric expansion coefficient of LBE and high boiling temperature (1 670°C) helps in this regard. The heat deposition by the proton beam raises the fluid temperature in the hot leg while the cold leg temperature is maintained through the secondary coolant flow in heat exchanger. The higher the temperature difference, greater will be the fluid flow. However, due to corrosion there may be an upper limit to the temperature difference that can be maintained. [5,6] This is a passive, self-driven flow system and hence conducive to enhancing the safety feature of the ADS. The main disadvantage of this system is the size of the target loop. In order to ensure that buoyancy head is adequate for required cooling, either the height or diameter of the loop becomes large. Another disadvantage with buoyancy driven system is the likely over shooting of the coolant temperature during start up or fast transients when sufficient buoyancy head is not available (this puts the limit on the rate at which beam current is increased during start up).

Flow under gas-injection enhanced buoyancy driven flow

In this system (see Figure 1b), the effects of natural convection are reinforced by way of mixing a gas to create two-phase flow in the riser leg, which increases available pressure head to drive the liquid metal flow. Since an inert gas is introduced in the liquid heavy metal, which separates out in the separator tank, it may be possible to use this gas loop to remove online, gaseous spallation products and vapours like polonium and mercury. In this configuration, it is possible to build a compact target loop system.

Figure 1. **(a) Buoyancy driven target module**
(b) Gas-driven target module



Also, the need for maintenance of inline dynamic machinery like pump is avoided. The gas injection helps in quicker start up of the flow. In fact one can have buoyancy driven target configuration with a provision to drive with gas during start up so that local overshooting of temperatures can be prevented. Gas driven system has been proposed by ANSALDO both for driving reactor coolant (LBE) and target consisting of LBE. [7]

Design of target loop

The target loop has been designed by using one-dimensional codes (1-D). These codes will be supplemented with 2-D (two–dimensional) and 3-D (three-dimensional) codes presently being developed for flow analysis in the spallation region along with nuclear high and low energy codes for spallation process. In this paper calculated values for 3 mA and 2 mA of a one GeV proton beam are presented. Since a GeV proton beam deposits around 66% of the beam energy, [8] 2 MW and 1.34 MW heat deposition has been assumed for 3 mA and 2 mA currents respectively. The penetration range of the proton beam is taken as 0.53 m. [8] The current density of the beam is taken as parabolic and the maximum current density at the centre is taken as 68 $\mu A/cm^2$ corresponding to 3 mA case. This decides the beam cross section which comes out to be 106 mm (the corresponding thermal load is within the capability of window configuration). The physical properties for LBE have been taken from Buono. [9]

Loop calculations for buoyancy driven window configuration

As shown in the Figure 1, the target loop is an axi-symmetric cylindrical device and the loop consists of spallation region, riser (annular cross-section of proton beam pipe and riser pipe) where liquid metal flows up after collecting the spallation heat directly from proton beam as well as heat deposited in the window by the beam. From the exit of the riser, the liquid metal flows into a heat exchanger located at the top of the downcomer. From the exit of the heat-exchanger, the liquid flows down in the downcomer (annular cross-section between downcomer pipe and riser pipe). The flow turns around and enters into the nozzle (spallation region) and into the riser (annular cross-section). Flow is assumed to be turbulent and incompressible except for variation of density with temperature (Boussinesq approximation). One-dimensional continuity, momentum and energy equations are used for the analysis. Pipe frictional pressure drop, gravity pressure head, pressure change due to velocity change, pressure drop due to sudden expansion and contraction etc have been incorporated in the code. The proton beam pipe diameter is determined based on the beam cross-section, which in turn is decided by maximum beam current density allowed by the window. Both riser and downcomer are assumed to be thermally insulated (by thin coating of appropriate ceramic material).

Heat-exchanger design

The coolant circuit envisaged for the Indian ADS target, at present, is a three-loop one. The target is cooled in the heat exchanger by LBE. This primary coolant in turn gets cooled in an air cooler in the tertiary loop through cross flow heat exchange (in case totally buoyancy driven loop is envisaged) or alternatively water will be used. The heated air is finally released to atmosphere through the stack. For the heat-exchanger for the target system, shell-and-tube counter-current configuration is taken. The outlet temperatures of the target material in the tube side of the heat exchanger is limited from melting point considerations and from the need for ensuring efficient heat transfer with the primary coolant through the entire length of the tube. Hence, the design inlet temperature is chosen to be around 275°C. For the primary coolant, the inlet temperature in the shell side of the heat exchanger is limited by its melting point. Temperature differences across the heat exchanger are restricted to a maximum of 200°C as higher temperature differences could lead to undesirable thermal stresses and corrosion problems.

The number of tube rings and total number of tubes in the heat exchanger are found from the annular dimensions. The shell side and tube side flow areas are calculated from the equivalent hydraulic diameters. For finding the length of the heat exchanger tubes for the required heat exchange, overall heat transfer coefficient, U_1 is first evaluated from the wall conductivity and local convective heat transfer coefficients, which are found from the convective heat transfer equation for liquid metals. The length of the tubes is then found from the heat flux equation.

Buoyancy driven loop

The sizing of the various components is carried out for the beam current of 3 mA current. This essentially decides the proton beam pipe diameter, which is taken as 0.128 m ID and 0.141 m OD (Sch.40 pipe). The riser diameter is chosen as low as possible to minimise frictional pressure drop (0.203 m ID and 0.219 m OD). The nozzle length is taken as 0.7 m. In Figure 2, the required heights for various downcomer diameters have been plotted corresponding to three ΔT cases (100, 150 and 200°C with inlet temperature of 275°C and the corresponding mass flow rates of 136, 91 and 68 kg/s respectively). Even though we have carried out the calculations for the case of 200°C temperature difference in the loop, detailed analysis will need to be carried out whether this much temperature difference can be maintained from corrosion point of view. For ΔT cases of 100 and 150°C, the maximum temperature of the container materials (except for window) being less then 450°C, it is possible to use austenitic steel (SS 316L). [10] Analysis has been carried out for different nozzle diameters (110, 100 and 90 mm). The main advantage of having smaller nozzle diameter is larger velocity of the liquid metal in the spallation region (which enhances the heat removing capability) with marginal increase in the pressure drop in the loop. For smaller nozzle diameters (less than the proton beam diameter), some heat will be directly deposited in the nozzle walls and some in the downcomer. However for nozzle diameter of 100 mm, since only edges of the proton beam is exposed, very little heat deposition is expected but with the advantage of higher target velocity.

We see that the required height steeply increases with the reduction of downcomer diameter. This is due to steep increase in the heat-exchanger pressure drop. [11,12] The slight increase in the required height with increase of downcomer diameter for the case of 150 and 200°C case (Figure 2) arises because of increase of entrance heat-exchanger pressure (the heat-exchanger dimensions remaining same for these cases). In the preliminary design of the Fast core, the available diameter for the target is 0.378 m. Hence we see that we cannot have buoyancy driven loop with ΔT of 100 (we require ~700 m height). Table 1 summarises major parameters of two possible configurations for buoyancy driven loop. In Case-1 the target requires marginally larger space than what is provided in the preliminary design of the fast core (0.406 m as against 0.378 m). In Case-2, the target is accommodated with in the space available in the core. The required height comes out to be around 12 m. The exact nozzle diameter and shape will be determined based on detailed flow analysis in the spallation region. Figure 3 compares the flow parameters when the same target is operated with 2 mA current (corresponding to 1.34 MW of heat). We see that, over all there is a reduction in the coolant flow rate and out let temperature. Reduction in the velocity in the spallation region may not affect the heat extraction since the heat densities also have been reduced (to be validated by CFD code).

Table 1. **LBE target parameters for buoyancy driven window configuration for 2 MW proton beam** (1.0 GeV energy and 3mA current)

Parameter	**Case-1**		**Case-2**	
Mass flow rate (kg/s)	91(nom)		68(nom)	
Inlet temperature (°C)	275		275	
Outlet temperature (°C)	425		475	
Proton beam pipe outer diameter (m)	0.141		0.141	
Riser outer diameter (m)	0.219		0.219	
Velocity in the riser (m/s)	0.534		0.403	
Downcomer outer diameter (m)	0.406		0.324	
Velocity in the downcomer (m/s)	0.115		0.191	
Heat-exchanger height (m)	1.116		2.308	
Frictional pressure drop across heat-exchanger (Pa)	3 735		19 858	
Funnel height (m)	0.7		0.7	
Funnel internal diameter (m)	0.10	0.11	0.10	0.11
Average velocity in the spallation region (m/s)	1.127	0.93	0.85	0.7
Total loop height (m)	8.95	7.4	12.10	11.5
Buoyancy pressure head (Pa)	16 325	3 735	28 680	19 858
Frictional pressure drop across the spallation region (Pa)	7 330	4 948	4 141	2 796

Figure 2. **Effect of downcomer dimensions on Buoyancy height**

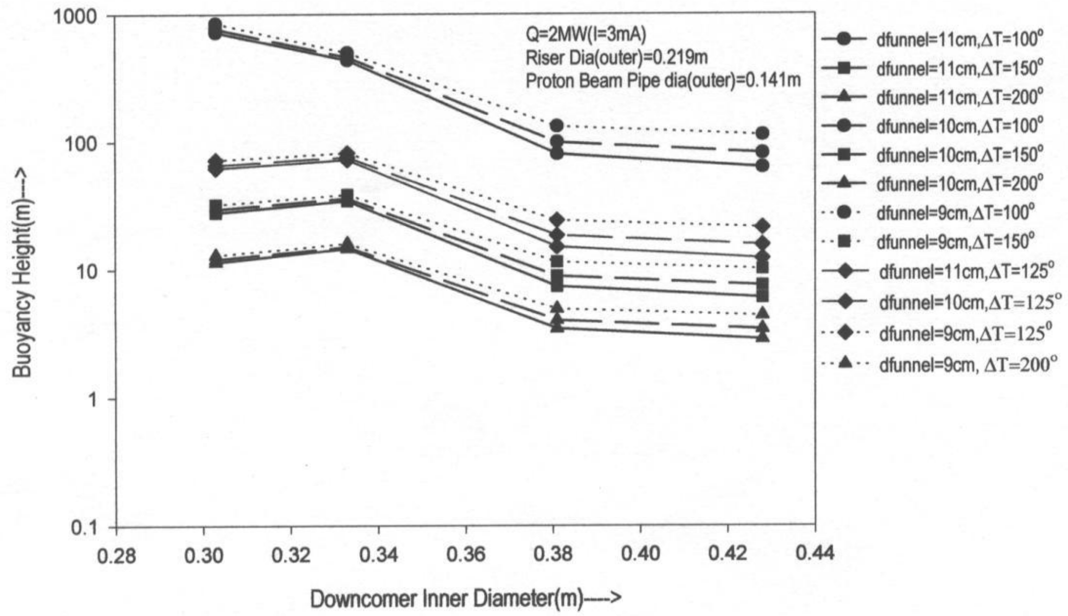
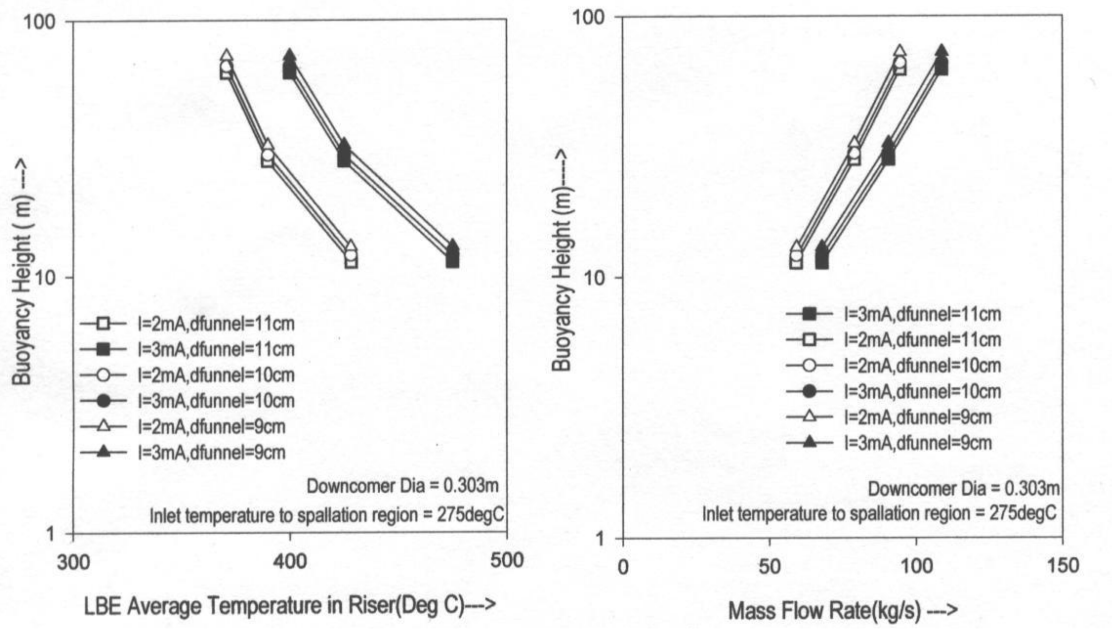


Figure 3. **Required Buoyancy height for various riser temperatures and target mass flow rates**



Gas-driven window configuration

The main difference in this loop is the presence of a mixer at the bottom of the riser (Figure 1b). Argon (or any suitable gas) at appropriate pressure and flow rate is introduced here. The gas is separated at the exit of the riser and liquid alone flows in to heat exchanger. For loop design, in addition to solving single-phase flow equations (similar to that for buoyancy system), two-fluid equations are used for two-phase flow. The two-phase model used here has been validated in a mercury-nitrogen loop set up in our institute. [13] The two-phase flow equations consist of continuity equations for liquid metal and gas, combined momentum equation and momentum equation for vapour.

Figure 4. **Effect of two phase height on gas flow rate**

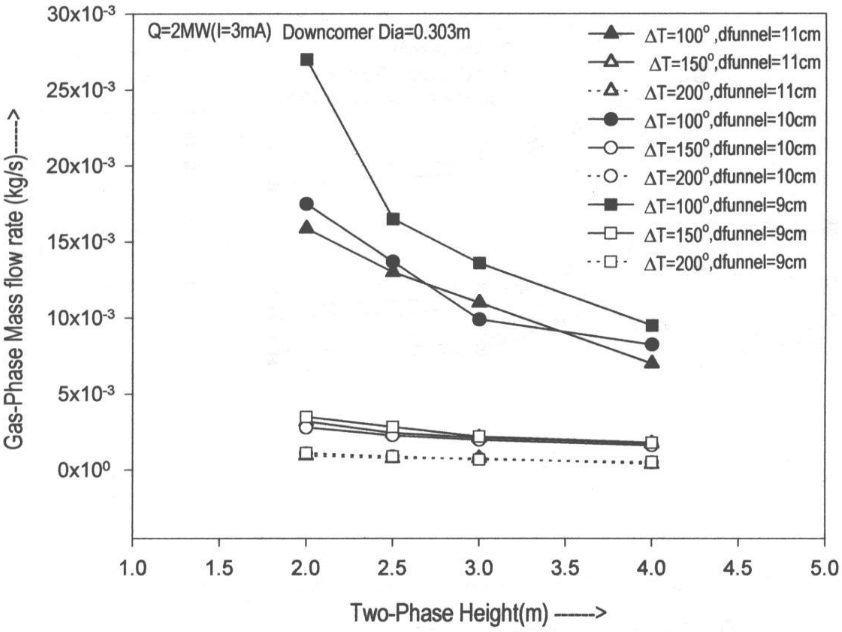
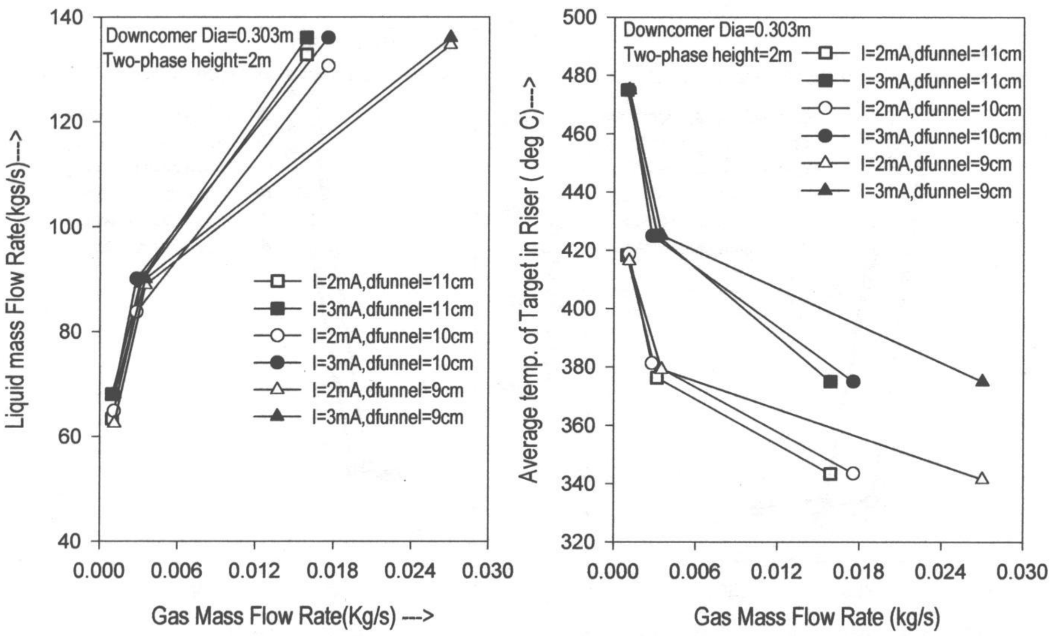


Figure 5. **Effect of proton beam current and gas flow rate on liquid mass flow rate and target riser temperature**



Different expressions for drag force have been used depending upon whether the flow is bubbly or churn or slug. Analysis has been carried out for different two-phase heights (2.0 to 4.0). The required gas flow rates have been plotted in the Figure 4 for different ΔT's. The maximum gas flow rate (Argon) required (corresponding to 2.0 m two-phase height and ΔT of 100°C) is only 16 g/s. The flow rate is 1g/s for the case of 4.0 m two-phase height and for ΔT of 200°C. Table 2 summarises the major parameters of gas driven target system. In Figure 5, the performance of the target loop when operated at 2 mA current case is presented (for the same gas flow rate). Since the liquid metal flow rate is primarily decided by the gas flow rate, the riser temperature is reduced because of reduction in the spallation heat. It is possible to design a more compact target module (smaller lateral dimensions) than the one presented here, by increasing the gas flow rate.

Table 2. **LBE target parameters for argon driven window configuration for 2.0 MW heat** (proton beam: 1.0 GeV and 3 mA)

Parameter	**Case-1**		**Case-2**	
Mass flow rate (kg/s)	91		136	
Inlet temperature (°C)	275		275	
Outlet temperature (°C)	425		375	
Heat-exchanger height (m)	2.143		1.886	
Pressure drop across HX (Pa)	3 2768		6 5451	
Proton beam pipe outer diameter (m)	0.141		0.141	
Riser outer diameter (m)	0.219		0.219	
Downcomer outer diameter (m)	0.324		0.324	
Velocity in downcomer (m)	0.254		0.382	
Funnel height (m)	0.7		0.7	
Funnel internal diameter (m)	0.11	0.10	0.11	0.10
Gas flow rate (g/s)	1.75	1.73	7.0	8.25
Gas pump power (w)	240	271.5	1 047	1 097
Length of 2-phase region (m)	4.0	4.0	4.0	4.0
Average velocity in spallation region (m/s)	0.93	1.127	1.4	1.68
Total loop height (m)	7.3	7.1	7.3	7.3
Buoyancy pressure head (Pa)	11 922	11 516	8 122	8 122
Pressure drop across spallation region (Pa)	4 948	7 330	11 082	16 420

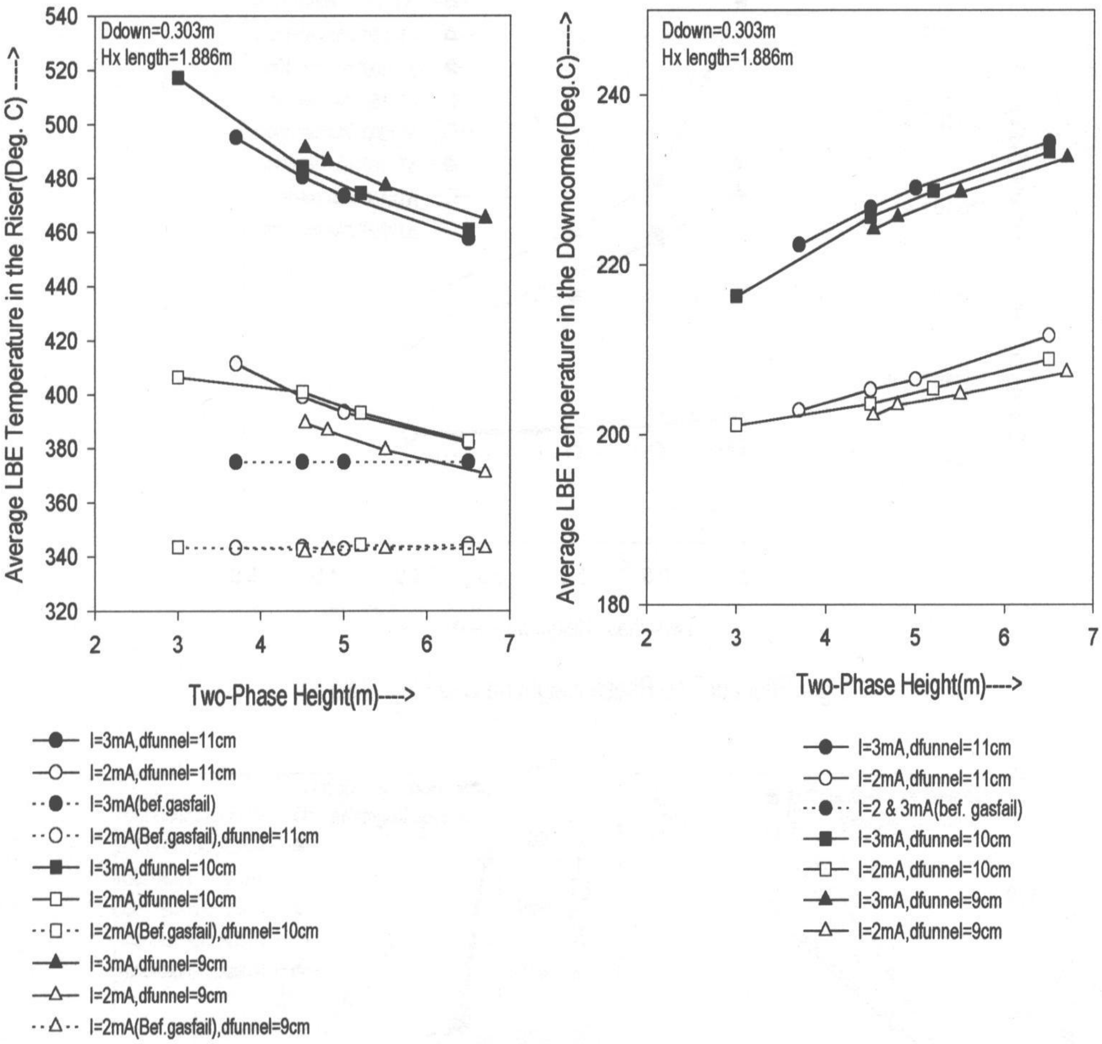
Effect of gas failure

In case gas flow fails, the liquid metal flow gets suddenly reduced to a very low value. However, subsequently the flow stabilises at a flow rate governed by buoyancy height available. In Figure 6, the temperatures attained by the target for various two-phase heights are summarised. For a height of 6.5 m, the riser temperature stabilises at ~458°C from ~375 when gas was driving (3 mA case).

Summary and conclusions

Preliminary studies related to thermal-hydraulics of spallation target for fast-thermal one-way coupled reactor based on LBE, have been carried out. Buoyancy driven as well as gas-driven configurations were considered for window configuration. The target parameters were determined based on one GeV proton beam of current 3 mA and complete loop analysis has been carried out. Parametric analysis for different flow rates, beam currents (2 and 3 mA and 1 GeV), geometry etc is presented and comparison made between buoyancy and gas-driven system target loops and it is found that compact target can be designed based on gas-driven system. However determination of the dimensions and shape of the spallation nozzle and the entrance of the flow to riser region will be based on detailed 2D/3D flow calculations. We are also setting up an LBE experimental facility to simulate thermal-hydraulics of target. Thermal and hydraulic simulation of target – proton interaction will be carried out using a plasma torch for window and electron beam for windowless systems (to study heat deposition on the surface) respectively to validate the codes that are being developed.

Figure 6. **Effect of compressor failure on LBE temperatures in donwcomer and riser**



Acknowledgement

The authors wish to thank Dr. N. Venkatramani, Head, Laser and Plasma Technology Division, BARC for his valuable suggestions during the preparation of the paper. Special thanks are also due to Dr. S.B. Degweker of Theoretical Physics Division, BARC for many useful discussions. We are also grateful to Dr. S. Buono of CERN for providing the LBE properties and heat density deposition data in the target due to Proton beam.

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