Accelerator Driven System Target Module Thermal Hydraulics Modeling Using RELAP5

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Abstract. Accelerator Driven System (ADS) has an ability to transmute radioactive waste with inherent safety. One of the key components of the ADS is the spallation target module. An ADS reactor operates under sub critical mode (k~0.95-0.98). An experimental LBE target system is currently being developed for coupling to 30MeV & 500micro-Ampere proton beam from cyclotron. The incident proton beam deposits approximately 15kW of heat in the window. Liquid metal LBE (Lead-Bismuth-Eutectic) is circulated to extract the heat from the window. A passive, gas injection-driven enhanced flow system to remove intense heat deposited in the window has been studied. Air-lift principle is envisaged to enhance coolant circulation by injection of gas in the riser. Detailed thermal hydraulic analysis of the upcoming experimental ADS facility (at BARC) has been carried out using Reactivity Excursion & Leakage Analysis Program (RELAP5). Transient cases considered include Beam shut off, nitrogen injection supply off and loss of cooling. For all the transient cases analyzed, time available for corrective action was predicted. CFD analysis was carried out to obtain window temperature distribution and stresses for various steady flow rates and bean scanning area.

INTRODUCTION

Accelerator Driven System (ADS) has gained immense importance due to its ability to transmute radioactive waste and its inherent safety (Rubbia et al.1995) [1]. An ADS consists mainly of three parts, i.e. accelerator system, spallation target and subcritical reactor core. Among them spallation target module is the most innovative component of the ADS. It constitutes the physical interface between the accelerator and the sub-critical reactor. It is simultaneously subjected to severe thermal-mechanical loads and damage due to high-energy heavy particles. Currently two types of generic target modules, i.e., window and windowless concepts have been proposed (K Biswas et al.) [2]. In the window target module, high-density liquid metal spallation target and proton beam pipe, under vacuum environment, are separated by solid window barrier through which proton beam passes to interact with the target and deposit a bulk of the beam energy as heat. For a typical window material and geometry, the proton beam deposits tens of kW of heat in the window for few mA of beam current (P. Satyamurthy etal [3]) Successful removal of heat deposited in the window by circulating target is one of the critical thermal fluid dynamic issues involved in target design. The velocity and temperature distribution in the spallation region crucially decide the capability of flow to remove the spallation heat. The problem is further compounded due to the requirement of relatively low velocities (to reduce corrosion and erosion and availability of low-pressure heads (for buoyancy system due to limitation on temperature difference between riser and downcomer) for liquid metal flow. Detailed experiments have been carried out to arrive at the optimum flow configuration that avoids flow stagnation and recirculation in the spallation region. Among circulation methods, pump driven circulation method is discarded to make the reactor inherent safety and to avoid pump related failures. To give reactor the characteristics of a passive system, natural circulation has been proposed. The problem of corrosion put an upper limit on temperature difference between cold and hot leg to ~ 150^{o}C which ultimately put a limitation on flow by buoyancy. Therefore, in order to assure the needed heat removal for window, the adoption of the air-lift principle is envisaged to enhance coolant circulation by the injection of gas in the riser. An experimental LBE target system is currently being developed for coupling to 30MeV and 500micro-Ampere proton beam from cyclotron. An attempt has been made to design a passive, self-driven flow system to remove the deposited heat from the window and hence conducive to enhancing the safety feature of the ADS. Thermal hydraulic safety analysis of the upcoming experimental ADS facility (at BARC) has been carried out using Reactivity Excursion & Leakage Analysis Program (RELAP5) & CFD codes. The case study for only buoyancy driven flow is compared with gas driven flow. Various transient conditions were also considered which are important from the safety point of view. It includes beam shut off, nitrogen injection supply off and loss of cooling, time margins available for corrective action were predicted.

DESCRIPTION OF EXPERIMENTAL LBE TARGET LOOP

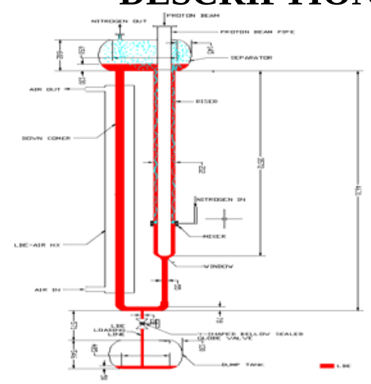

Fig 1. ADS experimental test loop

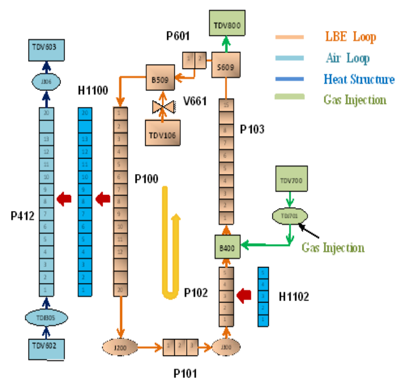

Fig 2. Nodalization for buoyancy

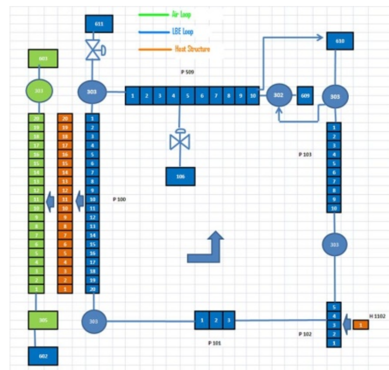

Fig 3. Nodalization gas driven

The height of experimental LBE circulation loop is ~ 7m, which would operate at ~ 220℃ with LBE flow rate of ~ 33 kg/s that would be realized through nitrogen injection (Fig 1). Major component of loop are window, flow region near the window, proton beam pipe, annular riser pipe, separator, mixer (gas injector), down-comer pipe, heat exchanger and dump tank. The dump tank is provided at the bottom of the loop, where the LBE is stored when the facility is not operated. The incident proton beam deposits 15kW of heat in the window it is removed by circulation of LBE. In the mixer, located below the riser pipe, nitrogen gas is injected. This gives rise to two phase mixture and consequently a density difference between the riser and down-comer pipes it leads to circulation of liquid metal in the loop. The riser height is designed in such a way that required flow rate of liquid metal is achieved. Together LBE and nitrogen enter the separator region located at the top of loop. Here the gas is separated due to buoyancy forces and taken out through a gas pipeline. The liquid metal flows down through the outer annular down-comer pipe heat exchanger which extracts the heat from the LBE. At the bottom of down-comer the liquid metal enters the spallation region & riser. Fig 2 shows nodalization scheme of the experimental facility for the buoyancy driven flow.

RESULTS OBTAINED FOR BUOYANCY DRIVEN FLOW

It is not feasible to have flow totally driven with natural buoyancy force alone. This may call for a very tall loop to enhance flow rates required for proper window cooling. Two cases have been discussed here i.e. 1) only with buoyancy driven flow, 2) Gas driven flow. The transient simulation includes loss of beam, loss of nitrogen injection. For buoyancy driven flow, beam power is kept constant at 15kW. LBE flow rate for the buoyancy driven case is around 4.2 kg/s at steady state. With gas driven flow we have unacceptable window thermal stresses if the beam scanned area is 5cm diameter or less. The CFD analysis indicated that for 10cm beam scanned area, buoyancy flow was adequate to keep the stresses in the window below yield point. However, due to higher stresses, the window life due to thermal cycling would be limited. Hence the requirement of gas driven circulation.

LIMITATION OF RELAP5 CODE:-

For the case of gas driven flow, nodalized scheme was modified (Fig 2, 3). Gas is injected at the bottom of riser through time dependent junction. Fig 2 nodalization scheme works fine only for buoyancy driven flow but for gas injection in the riser it does not quantify the quality & void for two phase volumes. To overcome this limitation, control variable are used to simulate two-phase pressure drop & head in the riser section and appropriately simulate the effect of gas in total LBE mass flow rate and heat transfer. This will produce the same effect if gas were injected. The two phase mixture density & pressure drop of LBE with gas is evaluated using void fraction correlation [4]. (Range of applicability is $0 < j_g < 0.4$ m/s, $0 < j_l < 0.9$ m/s, $\alpha \leq 0.4$). To insert the calculated two phase pressure drop in RELAP5 code, loop is divided into two parts from the point just above the riser. To make the bridge between two loops, Modified pressure and pressure drop in separator is added and inserted into the TDV610 (Fig 3). Mass flow rate of LBE from junction J310 is inserted into TDJ302. This causes RELAP5 to use the corrected pressure drop to simulate the rest of the loop. This arrangement will replicate the behaviour of riser if the actual gas were injected at the bottom of it.

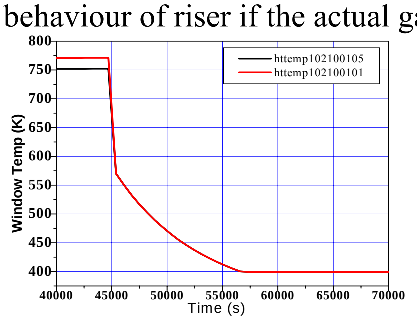

Fig 4. Beam off Window Temp

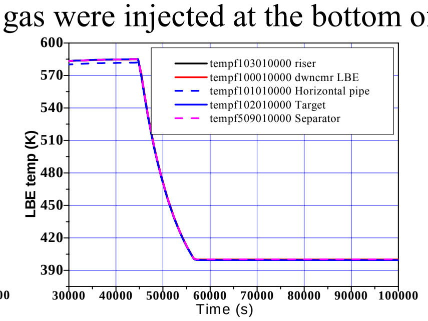

Fig 5. Beam shutoff: LBE temp

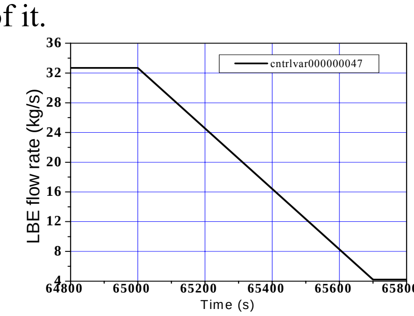

Fig 6. N_2 off LBE flow

INCORPORATION OF LBE HEAT TRANSFER CORRELATION

RELAP5 predicts lumped flow and windows temperature distribution. Thermal stress calculations require detailed flow distribution near the window region. Hence separate 2-D axi-symmetric CFD flow analysis was carried out to estimate the stresses for various flow rates and beam scanning area. RELAP5 uses heat transfer correlations which are valid for water-steam system. LBE heat transfer correlations were not introduced into the code along with thermodynamic properties. Therefore, like two phase pressure drop, LBE heat transfer coefficient also has to supplied from outside for appropriate heat transfer simulation in the secondary LBE cooling region. Control variable are used to calculate the LBE heat transfer coefficient. But it cannot be inserted in the RELAP5 executable code like the previous case, it can only be supplied in the form of general table as input time varying boundary condition using an iterative method. Therefore, multiple run were performed based on convergence criteria. In the first run, RELAP5 used its own heat transfer correlation but it also generates variation of LBE heat transfer correlation based coefficient with time. In the next run, LBE heat transfer coefficient obtained in the previous run is supplied through general table. Here RELAP5 uses previously calculated correct LBE based heat transfer coefficient and accordingly calculates heat transfer. These steps are repeated again till the convergence criterion is met.

Transient case:-

In an anticipated malfunction accidental scenario should not lead to an undesired situation in terms of window damage & solidification of LBE. Thermo mechanical failure of the widow is predicted using CFD simulation using the RELAP5 outcome. The beam scanning area variations considered was from 5cm, 5.5cm & 10cm diameter.

Proton beam Off: - Failure of proton beam leads to no heat deposition near the window region within 1 second i.e. loss of buoyancy driving force. Throughout the air injection rate is kept constant at 1g/s. LBE flow decreases as it becomes steady the new mass flow rate confirms that decrease in flow rate is only due to loss of buoyancy pressure head. Steep decrease in window temperature is observed as there is no heat deposition. Fig 4 shows window temperature Fig 5 depicts LBE temperature. The LBE temperature falls to 137 C which is very close to melting point of LBE (~ 125°C) in in approximately 12600 sec (3.5 hr) which gives enough time to take corrective action of controlling or stopping the gas injection.

N_2 supply off: - The next transient case is failure of N_2 supply system which drives the LBE flow. N_2 supply is tripped in ~50 sec. Here also the beam was not shut off and it continuously supplied 15kW heat to the window. As soon as gas supply is switched off, flow of LBE is reduced from 32.5kg/s to 4.1 kg/s within 53 seconds i.e. less than a minute (Fig 6). This will result in a gradual increase in window temperature. Enough time is available to shut off the beam following nitrogen injection failure. Thermo mechanical analysis using CFD simulation shows that with 5cm diameter beam scanning area the stresses are very high & not acceptable even with gas injection high LBE flow. With 5.5cm diameter beam scan area the stresses are acceptable with gas injection but not for buoyancy alone. With 10cm diameter beam scan area the stresses are acceptable even for large number of cycles.

CONCLUSION

The gas assisted enhanced natural circulation is essential to avoid window failure. RELAP5 code limitations for the given versions have been overcome by appropriate modeling of the user defined void fraction heat transfer and two-phase pressure drop. With 10cm diameter beam scan area the stresses are acceptable even for large number of cycles. With transient studies it was found that enough time wise margins are available to prevent undesired accident conditions & window degradation/failure under all the anticipated transients. Transient studies demonstrate the safety in operation & accidents for the ADS loop.

References:-

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