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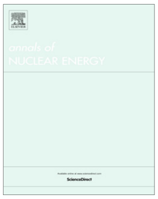

Integrated CFD investigation of heat transfer enhancement using multi-tray core catcher in SFR

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ABSTRACT

To render future SFR more robust and safe, certain BDBE have been considered in the recent years. A Core Disruptive Accident leading to a whole core meltdown scenario has gained the interest of researchers. Various design concepts and safety measures have been suggested and incorporated in design to address such a low probability scenario. A core catcher concept, in particular, has proved to be inevitable as an in-vessel core retention device in SFR for safe retention of core debris arising out after the severe accident. This study aims to analyse the cooling capability of the innovative design concept of core catcher to remove decay heat of degraded core after the accident. First, the capability of single collection tray is established and then the study is extended to two and three collection trays with different design concepts. Transient forms of governing equations of mass, momentum and energy conservations along with k-ε turbulence model are solved by finite volume based CFD solver. Boussinesq approximation is invoked to model buoyancy in sodium. The study shows that a single collection tray is capable of removing up to 20 MW decay heat load in a typical 500 MWe pool type SFR. Further, studies are carried out to improve the natural circulation of sodium around the source, in the lower plenum and to distribute core debris of the whole core to multiple collection trays. It is found that the double and triple collection trays can accommodate decay loads up to 29 MW. Provision of openings in the collection trays has proved to be effective in improving the heat transfer and sodium flow as well as in distributing the core debris to the successive plates. Detailed analysis of isotherms and velocity field in the multiple collection trays with openings reveals improved natural circulation in and around the collection trays in the lower plenum. A three tray core catcher device with multiple openings can accommodate the decay heat of whole core meltdown, without exceeding the safe temperature limits of structural material. Special attention has been paid to the space constraint in the lower plenum while incorporating the three tray core catcher device.

1. Introduction

To meet the ever increasing demand for energy and considering the global warming and its effects due to green house gases, it has become important to focus on nuclear options. Amongst the various types of reactors, fast reactors are designed with utmost inherent and engineered safety features to meet the growing demand for power and their added advantage in the transmutation of nuclear waste. Low probability events like whole core meltdown, with a frequency of occurrence $<10^{-6}$/ry, which are considered as Beyond Design Basis Events (BDBE) are analyzed with a view of defence in depth. In the recent past, various design concepts are suggested to minimize the consequences of BDBE. During a core melt-down accident, the molten fuel along with structural material in contact with coolant is expected to be fragmented and settled in the lower plenum within the main vessel threatening its integrity. A core catcher plays a very important role as an in-vessel core debris retention device aiding in Post Accident Heat Removal (PAHR) from debris by natural circulation of sodium, thus protecting the main vessel. Therefore, it is required to design an effective in-vessel core catcher for future sodium cooled fast reactors (SFR), which have the capacity to accommodate the mechanical and thermal load of whole core meltdown in case of a severe accident.

Total instantaneous blockage of one fuel subassembly and whole core melting due to a Core Disruptive Accident (CDA), demonstrating the capability of the core catcher to hold and retain the core debris in non-critical and coolable configuration are

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briefly explained by Gnanadhas et al. (2011). They have also highlighted PATH experimental facility to investigate heat removal by the natural convection with water as working fluid for code validation. Chellapandi et al. (2013) have analyzed the mechanical energy absorbing capacity of the main vessel, design pressure for Reactor Containment Building (RCB) and to demonstrate the functionality of Decay Heat Exchangers (DHX) after a CDA. They deal with the initiating events, i.e., Unprotected Loss of Flow Accident (ULOFA) and Unprotected Transient Over Power Accident (UTOPA) scenario that could lead to a CDA. Post accident heat removal during which decay heat generated by the core debris is removed until it becomes insignificant, is also discussed in their study.

Experimental and numerical investigations of melt fragmentation and settlement, morphological characteristics of debris and heat removal from the debris bed through DHX have been reported by Das et al. (2013). Their study focused on predicting the effect of reduction in the gap between Core Catcher Support Plate (CCSP) and main vessel on PAHR. Fragmentation phenomena and debris bed formation during core meltdown accident in SFR using simulated experiments have been investigated in the studies of Mathai et al. (2015). Their work focuses on debris bed formation and settling characteristics. Rajamani et al. (2016), studied transient flow and temperature evolutions in the reactor subassemblies and the sodium pool, coupled with the Safety Grade Decay Heat Removal System (SGDHRS). Their study was focused on establishment of natural convection in the intermediate sodium circuit of the SGDHRs after the air dampers are opened. They found that even in the worst case scenario of no forced cooling path being available the thermal inertia of the sodium pool within the main vessel and the passive cooling paths set up by natural convection in the liquid sodium and the air drawn from atmosphere are sufficient to safely dissipate the decay power of the reactor. The detailed CFD simulations for the passive decay heat removal of a sodium-cooled fast reactor were carried out by Hunga et al. (2011). They concluded that the passive reactor air cooling system can be an efficient system to remove decay heat through heat conduction, convection, and thermal radiation without the requirement of the operation of any active heat removal mechanisms. They also found out that, by adding an extended part of the reactor liner and/or core periphery, a recirculation would occur above the partition in the upper sodium pool and it was preventing the downward flow from partition to the core area and enhancing the convective heat transfer between the pools.

Core catcher concept can be either in-vessel (retention of core debris within the primary system) or ex-vessel (external to the primary system but within the containment). Both these concepts have been extensively used in water cooled reactors and a review on molten core cooling strategies for water cooled reactors is presented by Song and Suh (2009). In SFRs the coolant used is liquid sodium, which is reactive with air and water so in-vessel core catcher concept is the favourable option. Various design options of core catcher used worldwide are discussed by Jasmin Sudha et al. (2014). Their study suggested a multi layer core catcher concept for future sodium cooled fast reactors. They have proposed a design for whole core accident comprising of a top sacrificial layer of molybdenum, a middle refractory layer and a base layer made of SS316LN. However, the compatibility of the materials, used in the design, with liquid sodium ambient needs to be ensured with fabrication techniques for the lifetime of the reactor.

David et al. (2015) carried out numerical simulations of passive heat removal under severe core meltdown scenario in a sodium cooled reactor. They found that natural convection in the debris bed gets initiated within a few minutes after debris settlement and heat removal by the side pool plays important role. Their work also indicated that risk of main vessel failure would not be significant even if the DHX are not operational for a few hours after core meltdown. However, they studied the influence of heat flow paths on long term decay heat removal under severe accident by considering only 1/4th of the core meltdown with single tray core catcher design.

A conjugate heat transfer study of the turbulent natural convection of sodium in a cylindrical enclosure with multiple internal heat sources has been carried out by Sharma et al. (2008, 2009). Heat source was distributed uniformly on three plates with constant heat generation rate and it was concluded that entire core can be safely retained in the vessel. However, a simplified cylindrical geometry was considered for feasibility analysis of volumetric heat generating source in the adiabatic top and bottom boundary condition. The lateral wall of cylinder was assumed as isothermal. No attention was paid to the space availability in the lower plenum and to the path for allowing the core debris to reach the subsequent trays.

It is clear from the literature that significant work has been carried out in the recent past on PAHR with different design options and issues. However, the integrated analysis considering major internal components which can influence natural circulation in the pool during PAHR has not received adequate attention. Therefore, the present study focuses on integrated Computational Fluid Dynamics (CFD) investigations of heat transfer enhancement using innovative multi-tray core collection concept for future SFRs. A schematic diagram of passive heat transfer paths along with core catcher system of a typical pool type fast reactor is shown in Fig. 1. The study takes into account, the capability of a single tray core catcher and further extends the analysis to double and triple collection trays configuration with different geometrical considerations and alterations for improving the sodium circulation. Hence, the post accident heat removal from the destroyed core debris settled on these collection trays has been analyzed with emphasis on possible design modification in in-vessel safe core retention for whole core meltdown in the future SFRs.

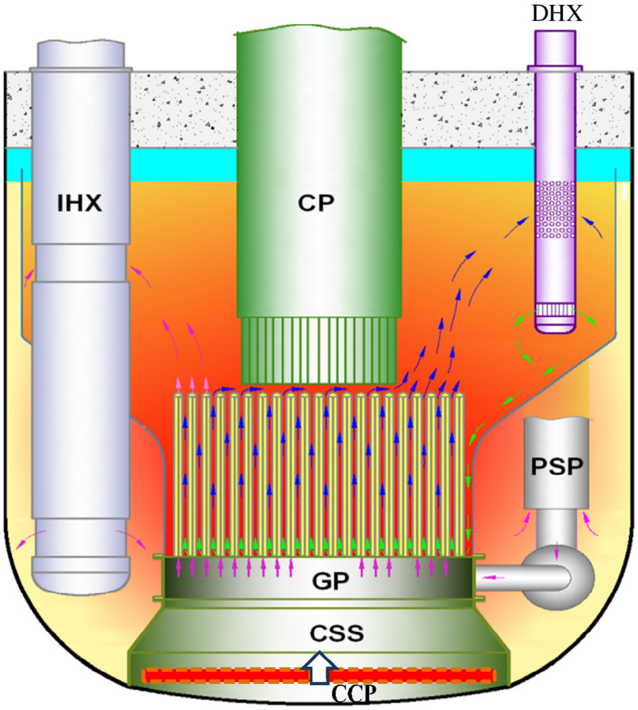

Fig. 1. Schematic diagram of passive heat transfer paths along with Core catcher (source Rajamani et al., 2016).