Progress in Nuclear Energy 105 (2018) 194–201

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Experimental simulation of downward molten material relocation by jet ablation of structures and fuel coolant interaction in a fast reactor

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In the remote chance of a core melt-down accident in a fast reactor, the molten corium from the fuel subassembly can come out in the form of a liquid jet due to the prevailing transient pressure. This high temperature jet is capable of causing local breaches on horizontal solid structures such as the grid plate with which they come into contact inside the main vessel. After penetration through the plates, the molten jet undergoes fragmentation in the bulk coolant available below the grid plate, in the lower plenum and settles on the core catcher. Experimental investigation of molten material relocation in the downward direction is carried out with a wood's metal jet impinging on a pair of solid wood's metal plates. The wood's metal alloy is heated electrically to about 300 °C inside the melt chamber and released through a nozzle to impinge on the dry plates mounted on rigid supports and allowed to pierce through the plates. The jet then gets quenched in bulk water contained in the experimental vessel. The trajectory of vertical jet impinging on the set of two parallel horizontal plates is captured using a high speed camera. Thermocouples are placed on the top and bottom surface of the plates to assess the temperature evolution. The breach area formed on the plates by the hot molten jet is assessed from the experiments. The initial pressure of the liquid jet is varied from 0 bar to 2 bar gauge pressure. The mass of the debris collected on the breached wood's metal target plates and the stainless steel collector plate gives evidence that the entire molten mass of jet does not reach the bottom collector plate but gets distributed on all the plates. The particle size distribution is obtained for the fragmented wood's metal debris settled on the collector plate. It is observed that the mass median diameter of the fragmented particles and porosity of the debris bed decreases as the jet release pressure is increased. An empirical correlation between the particle size represented by the mass median diameter and the initial pressure of the jet is obtained.

1. Introduction

A fast breeder reactor is protected by two diverse, reliable and fast acting shutdown systems which are capable of shutting down the reactor on demand. Hence a core melt-down accident is a beyond design basis event with the probability of its occurrence being 10^{-6}/reactor year (Kumar et al., 2005). Due to the highly reactive nature of sodium coolant, in-vessel core debris retention has to be ensured for a fast reactor. Therefore, the core catcher which is an engineered safety feature is provided inside the reactor main vessel to protect the main vessel from intense thermal loads. The molten core material relocation in the lower sodium plenum of the reactor vessel following a severe accident and its settling behavior on different structures and the core catcher are important events to be analyzed for efficient and robust design of the core catcher. The mechanical and thermal load on the core catcher depends on the fraction of core debris settling on it. The representation of the molten degraded core and the core debris settling on the grid plate and the core catcher is shown in Fig. 1.

The molten fuel can reach the grid plate either in the form of fragmented debris or in the form of a liquid jet. It depends on whether the molten fuel is quenched by liquid sodium within the active core region. Supposing that it gets fragmented by liquid sodium, the nuclear fuel settles as a debris bed on the grid plate. In such a case, the decay heat generating fuel debris can melt the grid plate gradually. The molten material relocation time to the core catcher has been estimated by numerical heat transfer study by Sudha and Velusamy (2014) for Indian FBR and by Voronov et al. (1994) for the Russian BN 800 reactor.

On the other hand, if there is large reactivity addition rates in the fuel subassemblies, there is a possibility that liquid sodium is

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https://doi.org/10.1016/j.pnucene.2018.01.010
Received 24 March 2017; Received in revised form 24 December 2017; Accepted 30 January 2018

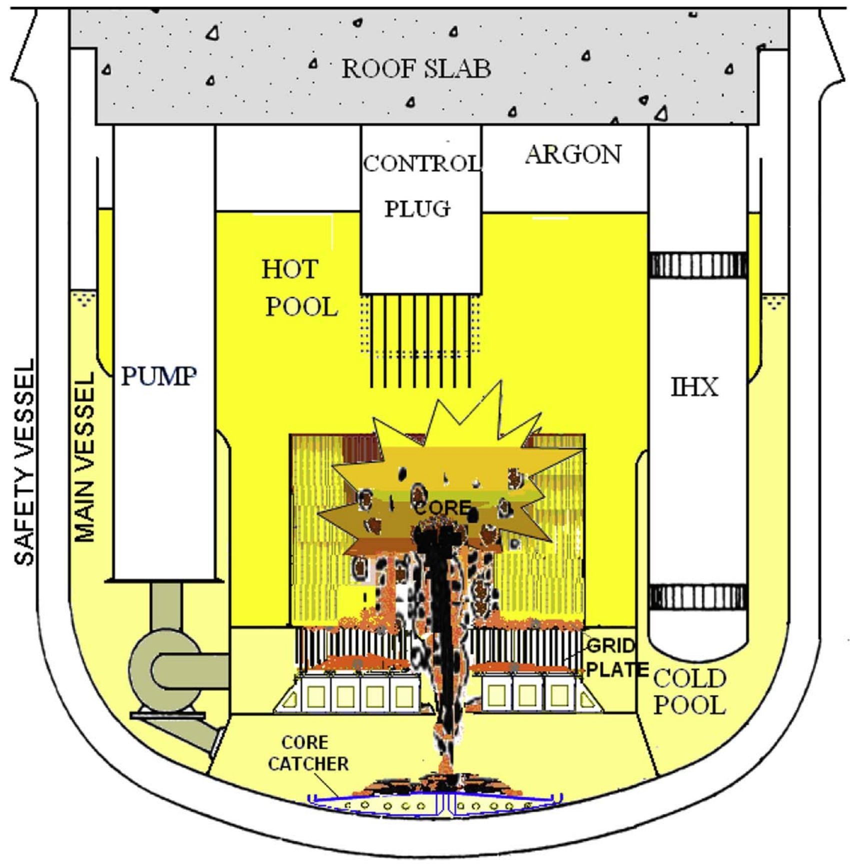

Fig. 1. Pictorial representation post-accident molten material relocation.

vapourized in the vicinity of the participating subassemblies leaving no scope for quenching of corium within the core. It is conservatively assumed that the time scales are short such that reflooding of the sodium from the surrounding area does not happen before the jet impinges on the plate. In this case, corium can come as a jet and hit upon the grid plate leading to local breaching of the plate. Here, unlike the first case, the contact area is localized. The heat transfer rates are very high for jet impingement and hence the time taken to breach the grid plate will be less than that required in the case of normal melting. Therefore, the objective of this present experimental study is to simulate substrate ablation due to a hot molten jet impingement in the absence of coolant and the molten jet is subsequently quenched in water. However it is to be noted here that the experiments carried out are not exact scale model experiments for the reactor accident, but they are carried out with a view to simulate and understand the combined events of jet ablation of solid structures and subsequent fragmentation in bulk coolant. Since the grid plate assembly consists of top and bottom plates, a pair of parallel plates separated by a distance is used in the experiments. Dummy stainless steel sleeves are placed on the wood's metal plates to simulate the presence of unaffected neighbouring blanket subassemblies in the reactor core. The effect of the initial pressure of the jet and the presence of solid obstructions in the path of the jet on the mass distribution and size distribution of the fragmented debris is obtained from the experiments.

2. Literature review

A review of heat transfer data for single circular jet impingement is made by Jambunathan et al. (1992) in his article. Experimental data for the rate of heat transfer from impinging turbulent jets with nozzle exit Reynolds numbers in the range of 5000–124,000 have been collated and critically reviewed from the considerable quantum of literature available on the subject. The review also suggests that the Nusselt number is independent of nozzle-to-plate spacing up to a value of 12 nozzle diameters at radii greater than six nozzle diameters from the stagnation point. The stagnation point flow field is analyzed extensively for submerged jets by Liu et al. (1993). Air jet impingement heat transfer experimental studies have been reported by Lytle and Webb (1994) at low nozzle-plate spacings. The stagnation Nusselt number was correlated for nozzle-plate spacings of less than one diameter. The customary Nusselt number dependence on square root of Reynolds number for impinging jet was observed by them. Lienhard (2006) in his paper has summarized theoretical and experimental results for laminar stagnation zone for a circular free impinging jet including Nusselt number correlations. Splattering of turbulent jets is also discussed in that work.

Buchlin (2011) in his paper deals with heat transfer by convection between impinging gas jets and solid surfaces. Experimental data obtained from infrared thermography are compared to CFD simulations. Abishek and Narayanaswamy (2012) have studied coupled effects of surface radiation and buoyancy on jet impingement heat transfer with air jets in laminar regime. Recently developed techniques in the field of modern experimental thermo-fluid-dynamics, namely infrared thermography and Particle Image Velocimetry (PIV) along tomographic PIV and their relevance to jet impingement heat transfer have been discussed in the review by Carlomagno and Ianiro (2014). Selvaraj et al. (2016) have carried out both experimental as well as CFD studies for the conceptual design of helium circuit for cooling irradiation target specimens. In the above cited literature, jet impingement has been used as a tool to enhance heat transfer.

Next, a review has been made on a few experimental studies where the main focus is erosion of substrate plates by molten jet. Sienicki and Spencer (1985) from ANL experimentally investigated the molten core downward progression in a LWR with thermite simulant jet, with an