Nuclear Engineering and Technology xxx (2017) 1–9

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

Investigation of molten fuel coolant interaction phenomena using real time X-ray imaging of simulated woods metal-water system

Avinash Kumar Acharya, Anil Kumar Sharma*, Ch.S.S.S. Avinash, Sanjay Kumar Das, Lydia Gnanadhas, B.K. Nashine, P. Selvaraj

Fast Reactor Technology Group, Indira Gandhi Centre for Atomic Research, HBNI, Kalpakkam 603102, India

A R T I C L E I N F O

Article history:
Received 7 February 2017
Received in revised form
28 June 2017
Accepted 3 July 2017
Available online xxx

Keywords:
Image Processing
MFCI
Real Time X-Ray Imaging
Vapor Phase Imaging

A B S T R A C T

In liquid metal fast breeder reactors, postulated failures of the plant protection system may lead to serious unprotected accidental consequences. Unprotected transients are generically categorized as transient overpower accidents and transient under cooling accidents. In both cases, core meltdown may occur and this can lead to a molten fuel coolant interaction (MFCI). The understanding of MFCI phenomena is essential for study of debris coolability and characteristics during post-accident heat removal. Sodium is used as coolant in liquid metal fast breeder reactors. Viewing inside sodium at elevated temperature is impossible because of its opaqueness. In the present study, a methodology to depict MFCI phenomena using a flat panel detector based imaging system (i.e., real time radiography) is brought out using a woods metal-water experimental facility which simulates the UO_2-Na interaction. The developed imaging system can capture attributes of the MFCI process like jet breakup length, jet front velocity, fragmented particle size, and a profile of the debris bed using digital image processing methods like image filtering, segmentation, and edge detection. This paper describes the MFCI process and developed imaging methodology to capture MFCI attributes which are directly related to the safe aspects of a sodium fast reactor.

1. Introduction

Studies related to the consequences of a molten fuel coolant interaction (MFCI) and safe retention of core debris after an MFCI are very important for the safety of plant personnel [1]. These data are helpful for development of a code to study the thermal hydraulics of severe accident scenarios in sodium fast reactors and to devise a system to retain the entire core debris. The present study is focused towards development of an imaging technique which will be able to depict the MFCI process consequent to severe accidents for sodium fast reactors. The technique, although developed for a particular experiment, can be used as a generic case of under sodium viewing.

The main challenges in imaging of an MFCI inside sodium are opacity, high temperature, and fast processes like solidification and fragmentation. Park et al [2] performed a quantitative visualization of the rapid fragmentation process of a high temperature melt drop of tin (0.7 g at 1,000°C) employing continuous high speed X-ray and photography. Their developed methodology could capture large steam air pockets attached on the top of the melt drop in the explosion interaction zone. Matsuo et al [3] conducted an MFCI experiment with uranium alloy and water. They captured visual data using a high speed video camera and found it very useful in defining MFCI characteristics. They also described characteristics of the frontal velocity of the molten jet into a stagnant water pool. The visual images showed that the jet breakup length depends on the injection nozzle diameter and is independent of the jet penetration velocity. Hansson [4] studied the dynamics of the hot liquid (melt) droplet and the volatile liquid (coolant) in the Micro-Interactions in Steam Explosion Experiments (MISTEE) facility. They investigated well controlled, externally triggered, single-droplet experiments, using a high-speed visualization system with synchronized digital cinematography and continuous X-ray radiography. Magali et al [5] studied fuel coolant interaction phenomena for pressurized light water reactor in their KROTOS facility, France under the SERENA program. They developed a methodology to capture the interaction mechanisms between the different components of the system (the hot molten pool, the liquid water, the generated fragments, and

* Corresponding author.
E-mail address: aksharma@igcar.gov.in (A.K. Sharma).

http://dx.doi.org/10.1016/j.net.2017.07.003

Please cite this article in press as: A.K. Acharya, et al., Investigation of molten fuel coolant interaction phenomena using real time X-ray imaging of simulated woods metal-water system, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.07.003

steam) from generated experimental data and calculation analysis. They were able to film the fragmentation of the melt within the test chamber using an X-ray radioscopy system. Potter et al [6], using microfocus X-ray imaging, studied defect formation in porcelain ceramics during drying. The onset of cracking, and hence the critical moisture content, can be established nondestructively by means of X-ray microfocus imaging. This imaging helped in precise determination of the time to formation of the first crack, even if that occurs internally. This is found to be more reliable than alternative optical means which rely upon externally visible fractures to determine the time to failure. It is concluded by them that MFX imaging can be used for online process control as a robust means of detecting the occurrence of fractures and voids within a body. Loewen et al [7] measured two dimensional distribution of molten lead interaction with water using application of continuous high and low energy X-rays. This technique depicted the three phases present in the process spatially and temporally. Munshi et al [8] described the role of tomography in void fraction measurement for a steady-state mercury loop. The paper reported very accurate measurements for void fractions present in the flow channel. The computed tomography-based imaging is useful in volumetric mapping of the process as compared to conventional radiography. However, the computed tomography technique is intricate in studying transient processes and is still evolving. Saksena et al [9] compared the void distribution in the riser leg of a mercury-nitrogen flow system obtained by gamma-ray tomography (experimental) and the FLUENT code (simulation). A comparison of the predicted and the experimental results shows that experimental numbers are consistently lower than numerical predictions.

From the above literature, it is clear that the determination of important attributes for MFCI, which are jet breakup length, fragmentation profile and noncondensable gas generation, is very important. However, the flow visualization for the MFCI process is scarce. Therefore, a woods metal water system has been used to develop and qualify the methodology to capture all attributes of MFCIs. The objective of the present study is to investigate the real time radiography potential in defining MFCI attributes for a woods metal water system and finally to develop imaging techniques for MFCIs in liquid sodium, which is an opaque medium.

2. Materials and methods

It is seen from literature that real time X-ray imaging is useful for depiction of an MFCI process. Hence, this study is performed for qualification of real time X-ray imaging system to understand the MFCI process. Water has been chosen as a simulant to replace sodium because of their similar attenuation curves generated by NIST [10,11].

2.1. Imaging principle

X-rays are a form of electromagnetic wave which penetrates through matter. They form images based on attenuation caused by the material. The attenuation depends upon the material density and length traveled by X-rays [12]. This decrease in X-ray energy is represented as follows:

$$I = I_0 \exp(-\mu t)$$

where I is intensity of the emergent radiation, I_0 is the source intensity, t is the thickness of homogeneous material, and μ is a characteristic of the material known as the linear absorption coefficient. The coefficient μ is constant for a given situation, but varies with the material and with the photon energy of the radiation. The units of μ are reciprocal length (for instance cm^{-1}). The absorption coefficient of a material is sometimes expressed as mass-absorption coefficient (μ/ρ), where ρ is the density of the material. Both parameters can be tailored for the imaging requirements. The energy of the X-ray source is required to penetrate and form images in a system and is derived based on medium's steel equivalent thickness.

2.2. Experimental facility

The experimental setup consists of an X-ray imaging system and stainless steel (SS) cylindrical vessel integrated with a melt release system and is used to capture the images. The schematic diagram of experimental set up is depicted in Fig. 1.

2.2.1. Interaction vessel

A 7 mm thick SS cylindrical vessel with dimensions of 166 mm outer diameter (OD), 1 m length was used as an interaction tank for this experiment. A melt release system was integrated at the top of the cylindrical vessel. The system consists of an SS melt pot with a 600 W rated surface heater integrated with a high temperature SS valve. K-type thermocouples were used for temperature measurement of melt charge.

2.2.2. X-ray imaging system

The X-ray imaging system consists of a digital flat panel detector (DFPD) and constant potential 225 kV X-ray source. The screen size of the DFPD is 16 inches. The DFPD can acquire images with a maximum acquisition rate of 30 fps with 400 µm resolution. The attenuated X-ray energy corresponding to the object shape and density falls upon the DFPD. The X-rays which fall upon the scintillator screen of the DFPD are converted into different visible light intensities. These visible light intensities fall upon an amorphous silicon photo diode. The voltage formed as a function of X-ray intensities from a photodiode array forms the respective digitized 16 bit X-ray image. The DFPD sends image data to a personal computer over fiber optic communication via a frame grabber card. The DFPD is operated remotely through the device driver installed in the personal computer.

2.3. Procedure

The imaging of molten metal inside the interaction vessel is the main purpose for the present study. The simulant inside the vessel is imaged using the DFPD. The DFPD has been calibrated by an X-ray source with reference to the SS tank. After calibration, the DFPD is kept in such a way so that it covers the interaction region. Some 250 g of woods metal (melting point approximately 70°C) is heated up to 200°C and released into the water (at 30°C) filled in a tank with a remotely operated valve. The X-ray images were acquired at 25 fps with intervals of 40 milliseconds using a real time X-ray imaging system.

The acquired images contain important information regarding the complex process that takes place during the interaction. The raw images were captured, which depicts the presence of woods metal inside the water. From the raw images, it is difficult to interpret the process. Hence, these images were taken for image processing in sequence through image filtering, segmentation, and edge filtering for image analysis [13–15].

3. Results and discussion

X-ray images obtained using an X-ray source of 190 KeV, 5 mA exposure at different time intervals are shown in Fig. 2. These are acquired at 25 fps with 0.4 mm spatial resolution using a flat panel detector. These obtained raw images have poor contrast. It is

Please cite this article in press as: A.K. Acharya, et al., Investigation of molten fuel coolant interaction phenomena using real time X-ray imaging of simulated woods metal-water system, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.07.003