Nuclear Engineering and Design 332 (2018) 238–251

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Experimental and CFD analysis of the effects of debris deposition across the fuel assemblies

Muhammad Safeer Azam, Fenglei Niu, Da Wang, Weiqian Zhuo*

School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Keywords:
Debris
Fuel assembly
Pressure drop
CFD analysis
Porous medium

ABSTRACT

During a loss of coolant accident (LOCA) or a main steam line break accident (MSLB) in a pressurize water reactor (PWR), debris of different sorts like particulate, latent fiber or chemical nature might be generated due to jet impingement or ensuing, hot, pressurized steam leaking from the site of damage. This debris gets transported to the emergency core cooling system (ECCS) or the containment recirculation system (CRS) and might get deposited on the sump screens and causes a head loss. Some of these debris particles escape the sump screens and get access to the primary system through the bypass and thereafter challenge the core flow path and cause the head-loss across the fuel assemblies. The deposition of these debris particles in the fuel assemblies generates the possibility of hindering the long term core cooling (LTCC) of the nuclear power plant. The US Nuclear Regulation Commission (NRC) regulates the possibility of a commercial nuclear power plant to be able to maintain long term core cooling in case of a LOCA based event. In light of the aforementioned reasons the study of the debris particles inside the fuel assembly under different conditions becomes necessary to investigate the deposition of these debris particles in the assembly. This paper consists of two parts. The first part reports the experimental results carried out on an actual 15 × 15 experimental fuel assembly for the study of the effects of debris deposition on the pressure drop observed due to it. The second part reports CFD study of debris particles deposited on the spacer grid in the form of a continuous porous medium under different conditions. The study involves steady state (pseudo-transient) analysis of a scaled model of the fuel assembly with the variation of thickness of the porous debris bed, the inlet flow-rate of the fluid and the void fraction of the porous medium against the pressure drop observed.

1. Introduction

The emergency core cooling system (ECCS) works to cool the reactor core in the event of a postulated loss-of-coolant accident (LOCA). The long-term reactor cooling water of ECCS comes from containment sump. Thermal insulation material, pipe material and coating materials might get dislodged along with the high-energy steam or water jet, which could be the source of the debris particles that enter the ECCS. Usually, the containment sump contains one or more screens to prevent the components of the ECCS from debris, which could be washed into the sump (Andreychek et al., 2011). Most of the large sized debris particles are blocked by the sump screens. However, some of the smaller sized particles like fine fibrous and chemical precipitates, might get ingested into the ECCS and subsequently into the reactor coolant systems (RCS), which would affect and challenge the long-term core cooling (LTCC). US NRC had addressed this issue in Generic Letter 2004-02 (U.S. Nuclear Regulatory Commission, 2004) and emphasized the need for compensatory measures during the time of debris-generation. Also, France IRSN concluded that the sump screen blockage is a potential problem for the 58 existing PWR units (CSNI, 2004).

Keeping this in view the study of debris induced head loss in the fuel assemblies and the ECCS becomes very important so as to avoid another catastrophe from taking place. So far a lot a experimental facilities have been developed to study the effects of debris deposition across the fuel assembly during loss of coolant accident (LOCA). Los Alamos National Laboratory (LANL) has been supporting the NRC and provided the Generic Safety Issue GSI-191 report (Shaffer et al., 2005). Westinghouse has evaluated the AP1000 in-containment recirculation screens using particulate debris, fibrous debris and chemical debris, which has demonstrated the successful function of Recirculation Screens (CR) and in-containment refueling water storage tank (IRWST) screens under debris loading in LOCA condition (McNamee et al., 2009). In upstream effect, Zigler (Zigler et al., 1995) predicted the head loss across the fibrous debris bed formed on the strainer for Boiling Water Reactors (BWRs) in the report NUREG/CR-6224. Later, Park (Park et al., 2011) carried out the experimental studies to demonstrate that the correlation was

* Corresponding author.
E-mail address: 1162112006@ncepu.edu.cn (W. Zhuo).

https://doi.org/10.1016/j.nucengdes.2018.02.025
Received 5 November 2017; Received in revised form 12 February 2018; Accepted 16 February 2018
0029-5493/

Nomenclature

BN	Bottom nozzle
CDI	Continuum Dynamics Incorporated
DHLT	Debris head lost test facility
ECCS	Emergency core cooling system
FA	Fuel assembly
Gf	Glass fiber
Gw	Glass wool
KHNP	Korea Hydro & Nuclear Power
LOCA	Loss-of-coolant accident
LTCC	Long-term core cooling
NPP	Nuclear power plant
RCS	Reactor coolant systems
SAS	Sodium aluminum silicate
ΔP_{FA}	Total pressure drop in a fuel assembly [kPa]
A_{flow}	Flow area [m^2]
Q_v	Volumetric flow rate [m^3/h]
d	Fuel rod diameter [mm]
De	Hydraulic diameter of fuel assembly [m]
dP	Pressure drop [kPa]
K_t	Total resistance coefficient
p	Pitch of fuel bundle [mm]
u	Fluid velocity [m/s]
ν	Kinematic viscosity [m^2/s]
ρ	Density of fluid [kg/m^3]

conservative in predicting the head loss across NUKON™ debris beds, and extended the debris thicknesses up to a wider range (from 4 in theoretically up to 6 in). Saya Lee (Lee et al., 2014) suggested a modified head loss model for low Rem (1.81–21.70) and high debris bed porosity (between 0.98 and 0.99) in a horizontal pipe. Additionally, a compression model was developed to predict the thickness and the local porosity of a fibrous bed (Lee et al., 2015).

In real condition, there are some debris which might bypass the sump screen and transport into fuel assemblies, which could inhibit LTCC and cause the downstream effect during the operation of the ECCS. In response to the issue, Westinghouse has evaluated the AP1000 1/4 height fuel assembly head-loss with a spectrum of different flow rates, debris quantities, debris types, methods of debris addition and other experimental variables to ensure that the most challenging conditions would not impede LTCC (Ruth et al., 2010). AVERA has also performed a scaled 1/3 height mock-up fuel assembly test, with scaled flow rate and scaled debris load, and has demonstrated that the pressure drop across the FA does not approach the acceptance limit of 13 psi (Geiger et al., 2009). A debris effect study on the pressure drop of half-length mock-up PLUS7 fuel assembly of APR1400 has also been performed in Korea Hydro & Nuclear Power (KHNP) (Suh et al., 2015). The test shows sufficient driving force to maintain adequate flow rate when using different types of debris. Numerical simulation in RELAP5-3D has been performed for the debris-generated core blockage considering full core as well as core bypass blockage conditions (Vaghetto and Hassan, 2013).

In previous downstream effect studies, the scaled down FAs, 1/4, 1/3 or ½ lengths of a full FA, have been used, and lack the specific quantitative relationship between debris mass and pressure drop or resistance of the tested FA. The purpose of this study is to analyze the pressure drop observed in the CFD simulations for a debris bed, assuming that all the debris that enters the fuel assembly deposits across the first spacer grid in the form of continuous porous medium with constant porosity at a certain flow rate and bed thickness. This recorded data is compared with the actual experimental results, so as to observe the critical conditions for the pressure drop observed and the effects of the debris deposition under adverse conditions.

This work provides reliable and quantitative data for nuclear power

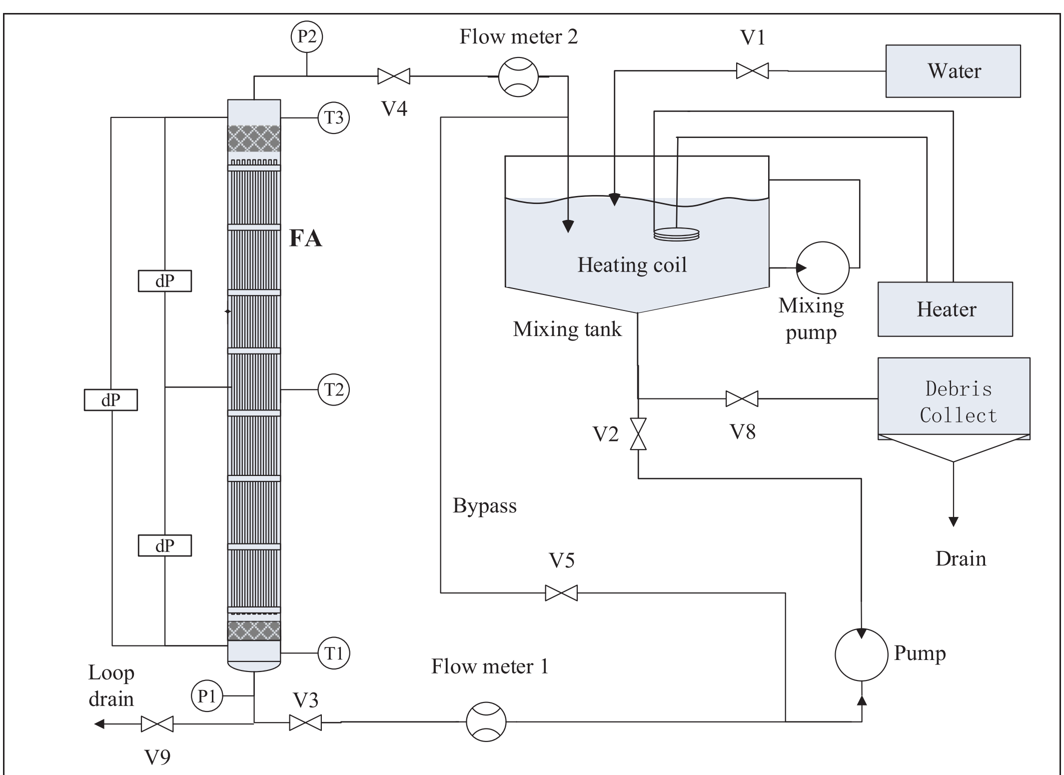

Fig. 1. Schematic diagram of the Debris Head Lost Test (DHLT) facility.