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Experimental investigation of partially ballooned fuel bundle under low injection flow rates

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ABSTRACT

A postulated loss of coolant accident in a PWR with failure of emergency core cooling systems causes loss of heat sink for the fuel pins. Overheating of the fuel pins and difference in the internal and external pressures leads to clad ballooning over large portion of the fuel pin length. The re-flood behaviour of ballooned fuel pins has been studied extensively in the past for ballooned heater pin configurations, with up to 20 cm ballooned length of the total length, and with water injection rates typically equal to Emergency Core Cooling System (ECCS) injection rates. An experimental setup is thus developed to study the effect of large extent of ballooned region (up to 60 cm of the total length) on the re-flood behavior. The experimental setup employs 5 × 5 matrix of indirectly heated, pre-fabricated ballooned fuel pin simulator (FPS) surrounded with 20 heated non-ballooned and 12 dummy FPS. The objective of this experiment is to study the effect of water injection rate and initial temperature on the quenching behaviour of ballooned heated pins under bottom re-flood condition. The water injection rates are kept lower (0.11–0.45 g/s per unit length per FPS) than the typical SAMG injection flow rates for typical PWR (1.12 g/s per unit length per fuel pin) and the initial temperatures range from 260 °C to 650 °C. In all experiments FPS are observed to be quenched, and enhanced quenching is observed in the ballooned region towards the exit of the region owing to lesser carryover. Increase in water injection flow rate is found to result in a transition in the rewetting pattern from conduction controlled rewetting to fluid controlled rewetting.

1. Introduction

Injection of water into the reactor core for post-dryout quenching is suggested as one of the Severe Accident Management Guidelines (SAMG) for Pressurised Water Reactors (PWRs). The effectiveness of this SAMG action depends significantly on the geometrical state of the fuel pins which, in turn, depends on the time of injection of water. Various stages of core degradation expected under accident condition without any mitigation measures are shown in Fig. 1. Escalation in the temperature of fuel pins prior to water injection and large pressure difference between the interior (fission gases) and exterior (primary coolant system) of fuel pins lead to ballooning of fuel pins over large lengths (shown as Large Scale Ballooning state in Fig. 1), causing reduction in flow area available for the fluid flow. Quenching of the core in such a state is governed by the extent of the ballooned region and flow blockages created due to ballooning. The quenching patterns of the non-ballooned as well as the ballooned fuel pins under re-flooding conditions have been extensively studied in the past for a Loss of Coolant Accident (LOCA) scenario. The quenching behavior of directly heated fuel pin simulators (FPS) conducted at facilities such as FEBA (Ihle and Rust, 1984), THETIS (Grandjean, 2007), FLECHT-SEASET (Lee et al., 1982) and indirectly heated FPS conducted facilities such as SEFLEX (Ihle and Rust, 1986), QUENCH (Sepold et al., 2007) for short lengths of ballooned portion (axial blockages) extending upto 20 cm (6% of total length) with around 90% of flow blockage (radial blockages) have been reported in the literature. Quenching of fuel pins under further stages of degradation is also studied in facilities such as PARAMETER (Dragunov et al., 2005), CORA (Veshchunov et al., 2005) and QUENCH (Steinbrück et al., 2010). It has been observed from the experiments mentioned above that a ballooned length of less than 10 cm of the total length does not alter the quenching patterns under re-flood conditions. However, a significant change is observed for ballooning up to 20 cm of the total length (Grandjean, 2007). Experiments performed in the JAERI facility also indicate the possibility of extended ballooning beyond 20 cm length (Parson et al., 1986). The experiments reported in the literature Ihle and Rust (1984, 1986), Grandjean (2007), Lee et al. (1982), Sepold (2007) are for design basis accident conditions, and hence the water injection rates considered in these experiments are

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Nomenclature

h	Heat Transfer Coefficient ($W/m^2 K$)
j	Superficial Velocity (m/s)
m	Mass (kg)
$\dot{m}$	Mass Flow Rate (kg/s)
t	Time (s)
A	Area (m^2)
C_p	Specific Heat Capacity (J/kg/K)
D_h	Hydraulic Diameter (m)
E	Fraction of flow entrained as carryover
H	Enthalpy (J/kg)
I	Current (A)
P	Power (W)
T	Temperature (K)
V	Voltage (V)
σ	Surface Tension (N/m)
ρ	Density (kg/m^3)
μ	Dynamic Viscosity (Pa.s)

Subscripts

c	Rod Centerline
e	External Surface of FPS
f	Fluid Phase Parameter
g	Gaseous Phase Parameter
i	Internal Surface of FPS
x	Distance from Beginning of Ballooned length (m)
s	Surface Parameter
Sat	Parameter at Saturation Condition

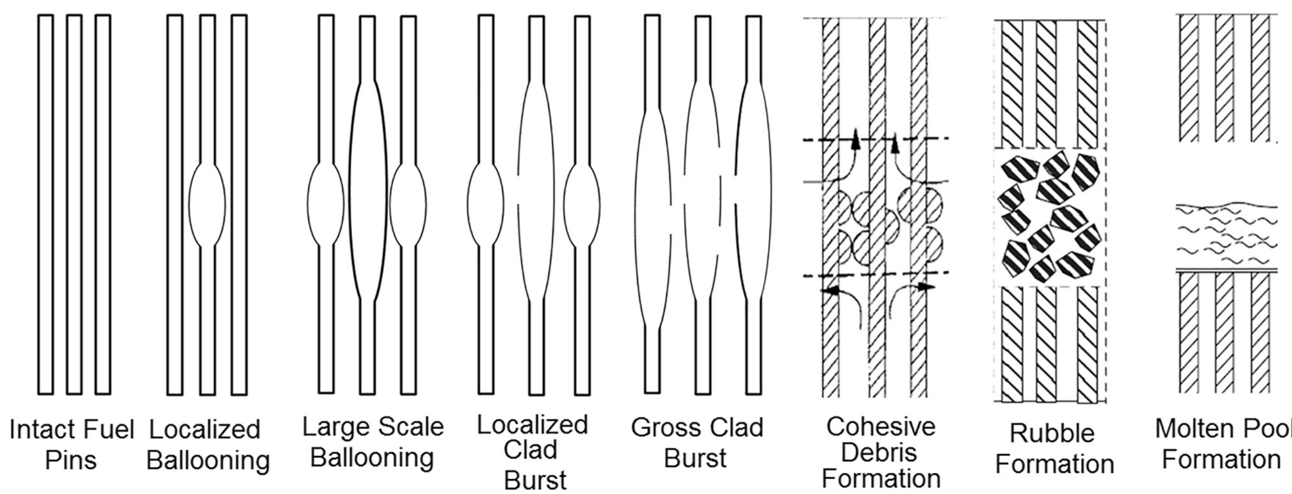

Fig. 1. Various Stages of Core Degradation under Un-mitigated Severe Accident Condition (MATPRO, 1997).

1 g/s or more per unit length of a single FPS. For an accident condition beyond the design basis, the flow reaching the core is likely to be lesser than the design basis value due to factors such as flow blockages and uncertainty over integrity of flow path. There is scare literature available on quenching of FPS with ballooning beyond 20 cm length and injection rates lower than 1 g/s per unit length of a single FPS as shown in Fig. 2 and Fig. 3 respectively.

An experimental setup is thus designed to study the quenching behaviour of FPS ballooned over 60 cm length. This configuration simulates the initial deformed core under severe accident condition. The range of injection rates is chosen to be 0.11–0.45 g/s per unit length for a single FPS, which is lower than the design basis injection rates. The effects of initial temperature of the FPS clad and water injection flow rate have been studied to understand quenching of FPS.

2. Brief description of the experimental setup

The schematic of the experimental setup is shown in Fig. 4. The experimental setup consists of FPS cluster having a combination of indirectly heated FPS and dummy (unheated) FPS, enclosed in a Stainless Steel (SS) shroud. Each FPS consists of a tungsten rod running through the center of the FPS, surrounded by annular pellets of alumina and SS tubes as clad. The FPS is electrically heated by passing current through the central tungsten rod. The central 25 FPS, marked with letter 'B' (Fig. 5) have a pre-fabricated ballooned portion over 60 cm. The ballooned region is created by using a higher diameter clad tube in the ballooned region as shown in Fig. 5. The heated ballooned FPS section is located at the center of the FPS cluster, in a 5 × 5 array laid in square pitch fashion, called the central zone (Fig. 5). Twenty heated non-ballooned FPS, marked with letter 'S' and twelve unheated dummy FPS, marked with letter 'D', are arranged uniformly around the central zone forming the peripheral zone. The 'B' pins and 'S' pins form the heated zone, as shown in Fig. 5. This configuration of a combination of ballooned central zone and non-ballooned peripheral zone represents a PWR core where initial degradation starts from the central zone under a

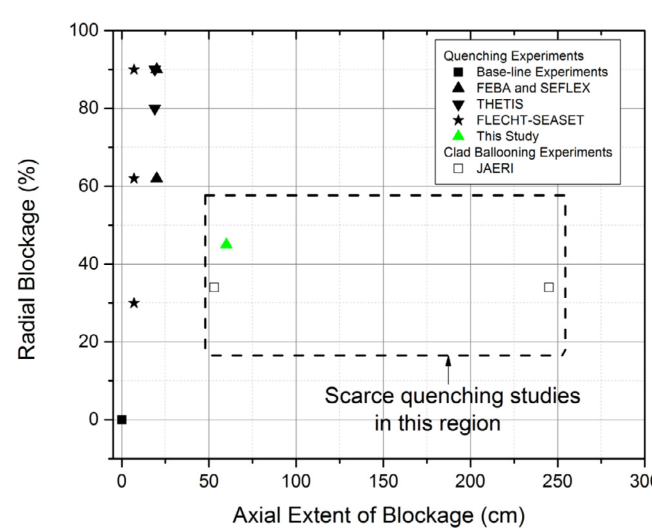

Fig. 2. Range of Radial and Axial Blockages considered for Quenching Studies.