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Radial jet induced rewetting study for heated rod

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ABSTRACT

Establishment of rewetting of hot nuclear fuel pins under a pipe break event is an important design aspect of Nuclear Power Plant (NPP). The successful rewetting of heated pins through Emergency Core Cooling System (ECCS) injection stands to be a major requirement as this action mitigates the accident progression. In Advance Heavy Water Reactor (AHWR), ECCS is designed to inject water from a central water rod of the fuel bundle in form of jets to rewet hot surface of fuel pin. This kind of design to reflood the fuel bundle is different than bottom and top spray reflooding practiced in PWR and BWR type of nuclear reactors. The success of the proposed ECCS injection type has been assessed in a separate effect test where the study has been carried out with a simulated single fuel pin. Influence of issuing radial jet on circumferential and axial conduction and associated rewetting pattern has been studied. As ECCS injection may take place at different decay power levels and at different fuel initial temperatures hence experiments are conducted at different power levels (212 W, 600 W, 780 W) and at different initial clad temperatures (400 °C, 600 °C, 660 °C). The injection flow rate has been kept constant at a design flow rate of 1.8 lpm for all the experiments. In all the experiments it is observed that a steep circumferential temperature gradient is established at the beginning of injection and the gradient comes down with the time advancement. A maximum gradient of 500 °C is observed for a short period of time (∼4 s) for the initial temperature of 660 °C. The influence of variation of jet velocity arising from height of it's injection is reflected on circumferential rewetting velocities which are found to vary from 2 mm/s to 10 mm/s. A correlation developed from experimental data has been proposed to estimate the average fuel temperature at any time instant during rewetting process. The study concludes that the design of multi point injection within the bundle will successfully be able to rewet the simulated fuel pin over the maximum period of time of ∼28.6 s.

1. Introduction

Rewetting of hot surface is a process in which a liquid wets a hot surface by displacing its own vapour which prevents the establishment of contact between the liquid phase and solid surface. Vapour layer formed between heated surface and coolant at high temperature leads to a poor heat transfer from solid surface to coolant. Once surface temperature is reduced to rewetting temperature, contact between coolant and surface is established which results in enhanced heat transfer and reduces the surface temperature.

It is essential to introduce few terms related to rewetting as the paper discusses the investigation out come with these terminologies. Following are the definition of the terms,

Rewetting: Re-establishment of coolant on dry heated surface is known as rewetting. It is possible when heated surface is below the Liedenfrost temperature by Duffey and Porthouse [1]. Fig. 1 illustrates a pool boiling behavior indicating Liedenfrost temperature. Experimentally, it has been found that Liedenfrost temperature of material SS-304 is nearly to be 310 °C, hence rewetting of heated SS surface at atmospheric condition starts from nearly 310 °C.

Reflooding: This is a situation where arrival of coolant to the heated surface happens, however arrival or flooding does not ensure cooling of the surface below Liedenfrost temperature.

Rewetting velocity: The definition is given as below,

$$\text{Rewetting velocity} = \frac{\text{Distance bewteen two consecutive points undergoing rewetting}}{\text{time period taken to rewet two consecutive points}}$$

Rewetting period: Time required from the time of arrival of coolant (reflooding) at a heated location to rewet the surface.

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Nomenclature

a', b', c', d', e'	constants in the rewetting correlation
A1, A2, A3	Rewetting correlation constant
c	clad specific heat (J/kg °C)
C_1,C_2	constant
d	diameter of fuel pin simulator (mm)
G	mass flow rate (kg/s)
K	thermal conductivity (W/m°C)
m	coefficient in rewetting correlation, a function of pressure
p	pressure (kg/cm^2)
p_o	reference pressure (70 atmosphere)
q	heat flux (W/m^2)
Q'''	volumetric heat generation (W/m^3)
r	radius of clad (mm)
r_2	outer radius of the inner tube (mm)
S	mass flux (kg/m^2)
S_o	normalized mass flux
t	time (s)
T	temperature of clad (°C)
$T_{coolant}$	temperature of coolant (°C)
T_{ave}	average clad surface temperature (°C)
T_{exp}	experimental Temperature (°C)
T_i	initial fuel pin surface (°C)
T_s	saturation temperature (°C)
T_{sp}	sputtering temperature (°C)
ΔT	subcooling (°C)
u	rewetting front velocity (mm/s)
U_u	uncertainty in rewetting velocity (mm/s)
U_u	error measurement in diameter (mm)
U_t	error measurement in time (s)
W	volumetric water flow rate (lpm)
X	vapour quality
ρ	clad density (kg/m^3)
θ	dimensionless initial surface temperature

The literature survey reveals that rewetting experiments mainly are carried out for bottom and top flooding for heated annulus geometry, single heater rod and cluster of heated rods to predict the rewetting velocity as a function of mass flow rate and surface temperature. Following sections discusses a review of work carried out for the bottom and top reflooding to highlight major findings on rewetting with these two modes of reflooding.

Duffey and Porthouse [1], Piggot and Duffey [2], Piggott and Porthouse [3] carried out experiment on bottom flooding with annuls geometry with surface temperature varying from 300 °C to 800 °C and with reflooding coolant rate variation from 0.006 lpm to 3.6 lpm. It has been found that by increasing reflooding rate by 600 times the rewetting velocity is enhanced by 50 times (1–50 mm/s). The rewetting velocity is found to be not in proportion to the reflooding flow rates. This illustrates that the energy removal process from the surface to coolant is a slow process owing to several heat transfer resistances that the cooling process encounters. The influence of degree of subcooling has been

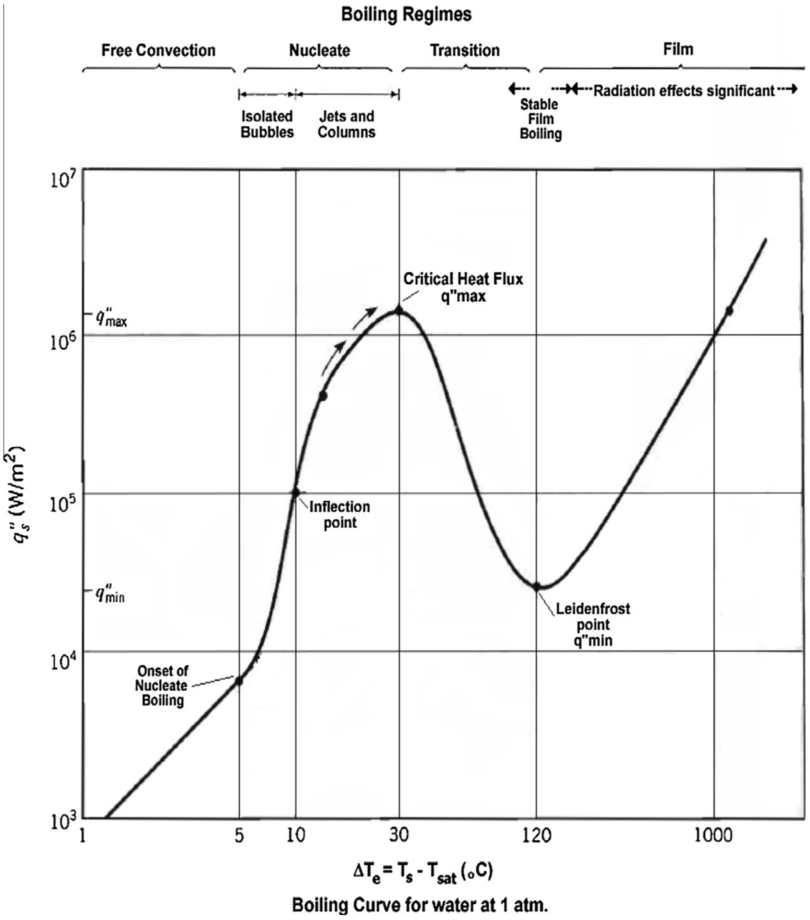

Fig. 1. Pool boiling behavior at 1 atm.