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A Comprehensive Study on Rewetting Behavior of Nuclear Fuel Rod Bundles during Loss of Coolant Accident

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Abstract

Rewetting is a process of repeatedly cooling hot surfaces. Rewetting is a very important content with thermal control for the safety of nuclear reactors during Loss of Coolant Accident (LOCA). A comprehensive study has been carried out over emergency core cooling of reactors and flow boiling regimes has also been depicted. Some valuable information drawn from overall achievement from this present investigation is the following the rewetting behavior is more or less linearly dependent on the operating conditions, but much effective response is observed with design parameters. In the present observation, it is very difficult to give a comment on the performance of the rewetting inside the rod bundle, as the flow is irregular and always distorted throughout the flow process in the rod bundle. It gives different information to one another location for each position of the rod bundled. The only valuable information drawn from overall achievement from this present investigation is the following; the rewetting performance can be improved significantly with the jet direction, with the proper jet diameter and certain maintenance on the liquid sub cooling and flow conditions depending on the initial wall temperature. Future works are depicted here which exclude the fundamental accomplishments from the present study.

Keywords: Flow boiling regimes; Rewetting; AHWR; Loss of coolant

Introduction

Rewetting is basically the re-establishment of coolant contact with a high temperature surface. In many industrial and several technological fields it occurs, like in metallurgical quenching, in nuclear reactor cooling, in cryogenic processes, in spacecraft systems and electronic systems thermal control and so on. In nuclear reactors during accidental scenarios a boiling crisis at high quality (dry out) occurs, leading to the disappearance of the liquid film wetting on the fuel clad [1]. The fuel elements in dry out will experience a significant rise in clad temperature [2]. In such scenario, an Emergency Core Cooling System (ECCS) is activated to cool the clad surfaces. Emergency core cooling is designed to remove the core heat by passive means in the case of a postulate LOCA. There are two common schemes for reflooding the nuclear reactors, namely top flooding (achieved by injecting water from the top as a falling film) and bottom flooding (achieved by an upward moving wet front due to coolant injection from the bottom of the core). The hypothetical concept of coolant flow behavior in the rod bundle of AHWR could be the combined of film falling and jet impingement. Heat transfer between the wall and the fluid is dependent on several factors. The flow channel geometry is of particular importance to the wall to fluid heat transfer. If the wall is a tube bundle, the heat transfer correlation will be very different from that used for walls that are parallel plates. Another important parameter in the determination of a wall to fluid heat transfer coefficient is the fluid flow regime. Bubbly flows have much more coolant in contact with the wall than post critical heat flux regimes and the velocity and volume of actual coolant is much different from the annular or slug regimes [3]. The rewetting phenomenon takes place during the transient cooling of a hot surface. When a hot surface at very high temperature is quenched with a stream of cold fluid, initially a vapor film is formed between the hot surface and the fluid layer over the surface [4-6]. Rewetting is a heat transfer process in which extremely rapid cooling results from bringing a high temperature solid into sudden contact with a lower temperature fluid. Heat removal from a hot surface by a liquid may be hindered if the surface temperature is high enough to allow the formation of a vapor layer, which acts as an insulator. Rewetting phenomenon takes place when the temperature of the surface cools enough to allow a change in the heat transfer regime from film boiling to transition or nucleate boiling [7].

Materials and Methods

Boiling heat phenomena

Boiling Heat Transfer (BHT) is used in a variety of industrial sectors, such as air conditioning, refrigeration, thermal power generation, nuclear reactors, chemical engineering, aircraft and spacecraft thermal management and high power electronics component cooling [8]. Boiling is a phase change process in which vapor is formed either on a heated surface and/or in a superheated liquid layer adjacent to the heated surface. Boiling process is subdivided into pool boiling and flow boiling. Pool boiling refers to boiling under natural convection conditions, whereas in flow boiling, liquid flows over the heated surface and external force are imposed. Forced flow boiling is subdivided into external and internal flow boiling. In external boiling, liquid flow occurs over an unconfined heated surface, whereas internal flow boiling refers to flow inside tubes. The three different boiling heat transfer mechanisms are nucleate boiling, where heat is transferred by means of vapor bubbles nucleating, growing and finally detaching from the surface; convective boiling, where heat is conducted through the liquid and this one evaporates at the liquid vapor interface without bubble formation and film boiling, where the heat is transferred by conduction and radiation through a film of vapor that covers the heated surface and the liquid vaporizes at the vapor liquid interface.

Rewetting behaviors

The phenomenon of the coolant coming into contact with the hot surface has been investigated by many researchers. Most researchers have described rewetting as the onset of transition or unstable boiling over a hot surface during the cooling from stable film boiling to nucleate boiling [9-11]. The rewetting temperature can be obtained from the cooling curve (wall temperature *vs*. time plot), where its slope is largest with the tangent to the curve and specifically from the intersection of the tangents to the wall temperature before and after the rewetting [12-15], considered the rewetting as the point of sharp drop in surface temperature during transient cooling of a hot surface. A certain period of time before initiating the wetting front movement is the wetting delay, shown in Figure 1. The quench front moves towards the downstream spatial locations, once the surface rewetting takes place in the stagnation region [16]. Rewetting velocity is described as the rate of movement of wetting front position over the heated surface. It gives an indication of how quickly the coolant contributes to effective heat removal from the hot surface. The rewetting velocity is calculated from the response of the respective wall points of the heated wall surface. The commonly adopted method to evaluate rewetting velocity is the time taken for rewetting to occur between two marked location points on the hot surface. The Δt represents the time period between two wall data point location and Δx is the distance between two data point location. The rewetting temperature is that temperature at which a liquid can re-establish on a dry hot surface. This is the maximum surface temperature at which the liquid solid contact occurs [17]. It gives an indication of wet patch spreading and from this location point wetting front movement starts. The wetting delay is a certain time interval between the application of the coolant and initiation of wet patch spreading on a hot surface [18]. This is the time taken for a surface to rewet after the application of water jet impinging onto the hot surface. This wetting delay period is also described as the resident time (*i.e.* time from when the jet strikes the surface to when the wetting front starts to move) [19,20]. The rewetting velocity is the ratio between the distances between the two local points to the time necessary for the rewetting front to move from one local point to the next local point. This is also defined as the speed of quench front movement over the hot surface.

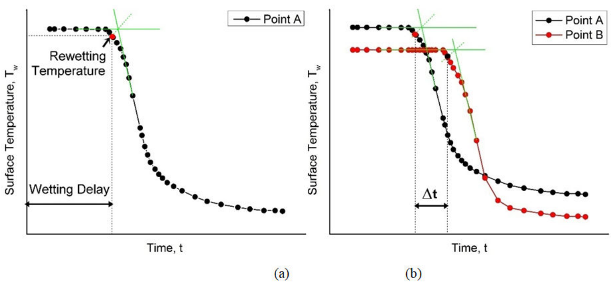

Figure 1: Method for determination of; rewetting temperature, wetting delay and rewetting velocity.

Rewetting of a hot surface is a process in which the liquid wets the hot surface by displacing its own vapor that otherwise prevents the contact between the solid and the liquid phase. The terms quenching, sputtering, Minimum Film Boiling point (MFB), return to nucleate boiling and Leiden frost phenomenon are often used interchangeably to refer to various forms of rewetting. Hsu studied the quenching of two metallic spheres, *i.e.*, stainless steel 304 and zircaloy 702, respectively, in natural sea water, compared with that in de-ionized water. Rapid quenching of stainless steel 304 and zircaloy 702 spheres at temperatures of about 1000°C in sea water and was investigated and adequately explained by the zeta potential effect created between the sea water and sphere as well as other forces between bubbles in water with dissolved salts. Such an effect prevents the stable film boiling and quenching starts from transition boiling even the surface is nearly 1000°C. The rapid quenching of the hot metal spheres in sea water demonstrated the benefits of nuclear power plant cooling using sea water, although the potential rapid corrosion of the metals, especially stainless steel, is also of significant concern. This study also confirmed the occurrence of rapid bubble nucleation for a moderate nucleation site density at a temperature close to 1000°C, which is much higher than the homogeneous or heterogeneous temperature of bubble nucleation predicted by classical nucleation theories. It was further observed that the vapor layer produced by film boiling was not immediately formed by contact of the liquid with the hot surface but through the coalescence of bubbles nucleated at very high temperature. Xu studied the influence of pressure and surface roughness on the heat transfer efficiency during water spray quenching of 6082 aluminum alloy. The results show that both the heat flux and heat transfer coefficient increase with the increasing of spray pressure. When the surface temperature is lower than 170°C, the heat flux, heat transfer coefficient and the maximum heat transfer coefficient decrease and then increase as surface roughness increases. However, when the surface temperature is higher than 170°C, the influence of surface is insignificant studied on the heat transfer performance of an Oscillating Heat Pipe (OHP) with self rewetting nanofluid. The maximal enhancement ratio of the self rewetting nanofluid is about 16% to that of the self rewetting fluid and about 12% to that of the nanofluid. The analysis of thermal physics properties indicates that the heat transfer enhancement of the OHP is caused by the comprehensive effects of high thermal conductivity and surface tension of the inverse Marangoni effect. Hu carried out boiling experiment to clarify the fundamental heat transfer characteristic and heat transfer enhancement mechanism of pool boiling with Self Rewetting Fluid (SRWF). The experimental results show that, the Critical Heat Flux (CHF) of the SRWF increased up to 2.52 times the CHF of water. It is also found out that, the bubble size of the SRWF is much smaller than that of pure water and the bubbles of SRWF were hard to coalesce, which is beneficial for the application in small thermal devices. Furthermore, when the heat flux was up to a certain value, the Micro bubble Emission Boiling (MEB) appeared in the SRWF. Kang, Quenching experiments were conducted to evaluate the Film Boiling Heat Transfer (FBHT); the heat transfer coefficient during FBHT, minimum heat fluxand minimum film boiling temperature were all larger with the Completely Wet table Surface (CWS) than with the Bare Zirconium Surface (BZS) or on the Roughed Zirconium Surface (RZS). Through high speed visualization, it is observed that intermittent wetting during FBHT resulted in an unstable liquid vapor interface in case of the CWS. Therefore, the remarkable ability of the CWS to supply liquid when in contact with the heat transfer surface resulted in clear enhancement of the FBHT performance (*i.e.*, increases in heat transfer coefficient, minimum heat flux and minimum film boiling temperature) studied a heat flux partitioning analysis of nucleate pool boiling on micro structured surface through infrared visualization technique. The experimental results indicate that the quenching heat flux and evaporative heat flux becomes dominant at high heat flux regime by numerous bubble generation and fast bubble growth. On the micro structured surface, the increased heating surface area by the roughness ratio instantly contributes the heat transfer performance enhancement and the area increase effect have to be reflected on the heat flux partitioning calculation conducted an experiment for film boiling of sub cooled liquids. They have describes the method and the results of experimental study of heat transfer during cooling the spherical patterns from nickel, stainless steel and copper with initial temperature above 700°C in water at schoolings up to 70 K. It is revealed that at high cooling rates the temperature field can lose its spherical symmetry, high temperature gradients are observed not only in the radial direction, but also along the surface. At high subcoolings the heat transfer regime of high intensity arises at the surface temperature 600°C-700°C that excludes a possibility of liquid/solid direct contact; heat flux density can be as high as 5-7 MW/m^2 Kozlov and Keßler studied an influenced on liquid quenching by surface structuring. It was found that the purposefully structured surface can affect quenching kinetic considerably. Chung investigate the heat transfer and boiling characteristics for the downward facing wall heating.

Results and Discussion

These results include temperature/heat flux histories, snapshots of bubble sliding/breakup/coalescence characteristics, relationship of Nussle number *vs.* Rayleigh number for the natural convection and boiling curves in the nucleate boiling regime. More oscillation is also measured for the forced boiling case than the pool boiling case due to the disturbance of injection flow. This finding is not similar to the boiling heat transfer in the normal heating layout investigated the effect of the several coolant injection systems carried out an experimental investigation of rewetting of AHWR rod bundle with radial jets studied influence of rewetting of AHWR fuel bundle. It has been observed that rewetting time of fuel surface temperature in case of cross flow modeling has been increased with respect to single volume. The rewetting pattern for a fuel pin simulator under radial jet cooling found to be different than bottom or top flooding case as cooling along the circumference is non uniform. The circumferential conduction at the plane of jet impingement is found to control rewetting period. A steep circumferential temperature gradient during the rewetting phase is found to exists, which may impose a thermal stress. It has been found that rewetting time depends on Fuel Pin Simulator (FPS) heated surface temperature and mass flow rate which is found to be similar in nature as observed for bottom and top re-flooding cases. An empirical correlation from the test data has been developed and the correlation can be used to predict fuel average transient temperatures of heat generating fuel element subjected to radial jet cooling. Further, Debbarma and Pandey have studied the effect of flow rates, jet diameters and proposed the three modes of jet directions in AHWR cluster. In the study the radial jet impinges of coolant into AHWR rod bundle has been evaluated using CFX code. The numerical approach is intended to evaluate the rewetting temperature, wetting delay and rewetting velocity. It was investigated with the various effect of flow rate, sub cooled, initial wall temperature, jet diameter and jet direction models to understand the mechanism of rewetting behavior during emergency core cooling in AHWR. Extensive studies on the rewetting of hot surfaces have been carried out from the earlier work. The fundamental characteristics of rewetting phenomena which dominating the rewetting temperature, wetting delay and rewetting velocity are highlighted here. The parameters that influence the rewetting phenomena are discussed in the following sub-sections. Details data of some experimental, numerical and analytical studies on top flow and jet impingement rewetting are summarized in Table 1.

Rewetting temperature

Rewetting temperature is one of the most critical terms and understanding the behavior of this term is required in engineering and scientific fields for the safety analysis during boiling crises in light water reactors (pressurized water and boiling water reactors). Hall conducted an experiment to study the boiling heat transfer during quenching of a cylindrical copper disk by a sub cooled, free surface water jet. The result is found that rewetting temperature increases with increasing jet velocity and increasing void fraction. Agarwal et al. conducted the experiments for the effect of jet diameters in the range of 2.5 mm-4.8 mm. A horizontal stainless steel surface at 800°C ± 10°C initial temperature was cooled by a round water jet. The water jet at 22°C ± 1°C temperature impinged onto the hot surface through tube type nozzles of 250 mm length. It was observed that for all the investigated jet diameters and Reynolds numbers, initially rewetting temperature remains unchanged in the stagnation region and then falls for the locations away from the stagnation point. A rise in the rewetting temperature has been observed with the increase in jet diameter and jet Reynolds number. The rewetting temperature is always the highest within the stagnation region. Further, Agarwal investigation has been performed to study the rewetting behavior for three different initial surface temperatures *viz*. 255°C, 355°C, 565°C. The rewetting temperature for the entire range of measured spatial location increases with the rise in surface initial temperature. In term of spatial variations, the rewetting temperature for the downstream spatial locations away from the stagnation point reduces for 255°C initial surface temperature, whereas it shows an increasing trend with 565°C initial surface temperature. At 355°C initial surface temperature no significant change in the rewetting temperature is observed for the entire range of spatial locations investigated. Further, Agarwal extended their work for the investigation of nozzle geometry on hot horizontal surface rewetting during water jet impingement cooling. The rewetting temperature at the stagnation point is approximately the same for the sharp edged and tube type nozzles.

Author(s)	Test section geometry	Materials of test cell	Coolant types	Coolant Flow Conditions	Sub-cooling range	Initial surface temperature range	Jet diameter range
Hall	Free surface, Circular Disk	Copper	Water	2.0 to 4.0 m/s	75°C	500°C to 800°C	5.1 mm
Agarwal	Free surface, Rectangular plate	SS-316	Water	0.92 to 8.40 m/s	± 22°C	± 800°C	2.5 mm to 4.8 mm
Piggott	Tube	Gold, Inconel	Water	5 to 15 g/s	5°C to 80°C	500°C to 800°C	1.5 mm to 3.0 mm

Mozumder	Free surface, cylindrical block	Copper, brass and steel	Water	3 to 15 m/s	5 to 80 K	250°C to 400°C	2 mm
Hossain and Hossain	Free surface, cylindrical block	Brass	Water	3 to 10 m/s	------------	250°C to 450°C	1 mm
Chen	Tube	SS-304 Inconel X-750	Water	10 to g/cm^2/s	10°C to 80°C	270°C to 800°C	----------
Carbajo	Cylindrical rod, 1-2-Dimentional	Zircaloy-2, SS-347, Inconel 600	Water	-------------	21°C to 144°C	204°C to 538°C	----------
Peng and Peterson	Free surface, flate plate	-----------	Water	0.1 to 37 gm/s	-------------	100°C to 800°C	----------
Filipovic	Free surface, Rectangular	Copper	Water	2.0 to 4.0 m/s	25°C to 55°C	850°C	----------
Saxena	Vertical annular channel	SS-304	Water	1 to 7 lpm	-------------	200°C to 500°C	----------
Hammad	Free surface, Block	Copper, Brass and Steel	Water	3 to 15 m/s	5°C to 80°C	250°C to 300°C	----------
Karwa	Free surface, cylindrical block	SS-304	Water	2.5 to 5 m/s	12°C to 70°C	885°C to 900°C	3 mm
Agrawal and Sahu	Vertical foil	SS-304	Water	---------------	± 28°C	150°C to 650°C	0.655 mm
Kumar	3-Dimentional, Fuel pin	------------	Water	---------------	300°C	400°C	----------
Anglart and Nylund	Circular channel, rod bundle (6 pins)	------------	Water	1112 kg/m/s	3.5 K	----------------	----------
Patil	AHWR fuel cluster	SS-304	Water	50 lpm to 83 lpm	18°C to 25°C	150°C to 400°C	2 mm

Table 1: Details of some experimental, numerical and analytical studies on top flooding and jet impingement.

The rewetting temperature for downstream spatial locations is always higher with tube type nozzles compared to sharp edged nozzles irrespective of the change in jet Reynolds number. Fan have studied the effects of surface wettability, from super hydrophilic to super hydrophobic, on transient pool boiling of water under atmospheric pressure were experimentally examined by means of the quenching method with hot stainless steel spheres. The wettability changes, with a contact angle ranging from nearly 0° to more than 160°, were realized by nanostructured coating on the spheres. The quenching cooling rate was slow down with increasing the contact angle as the vapor film was stabilized and retained by surface hydrophobicity even at very low wall superheats. Remarkable boiling heat transfer enhancement, with Critical Heat Flux (CHF) increase up to nearly 70%, was achieved for the super hydrophilic case as compared to the original hydrophilic baseline case.

Wetting delay

The determination of wetting delay is important for knowing how quickly a certain spatial location attains the rewetting condition after the application of a coolant on the hot surface. When the mass flux is increased and the other variables (electrical power, inlet fluid temperature and initial wall temperature) are kept constant, the time required to quench a particular axial location decrease. The wetting delay or quenching times do not appear to be directly connected with the times to reflood. As a consequence, quenching times are not connected with the peak cladding temperatures but only with the reflood flow rate; lower reflood rates clearly lead to longer quenching times. Piggott observed that the delay time is independent of jet size for a particular set. The wetting delay found to be varied with the strong function of water sub cooling, jet velocity, surface thermal conductivity, heat generation rate, jet impact angle and surface temperature. However, surface finish and rod size had little effect investigate the effect of sub cooled water jet during quenching of hot cylindrical blocks made of copper, brass and steel for initial surface temperatures from 250°C to 400°C. The jet velocity was from 3 to 15 m/s and jet sub cooling from 5 to 80 K with a jet diameter of 2 mm. Results show that the wetting delay increases with an increase in initial temperature. They also concluded with a statement that the wetting delay is a strong function of the properties of the solid material, sub cooling, jet velocity and initial surface temperature. Hossain and Hossain study has also focused on the wetting delay through jet impingement quenching of a high temperature brass block. The observations show that the wetting delay increases with increasing initial temperature. Agarwal et al. observed that the wetting delay period increases for the locations away from the stagnation point. For the downstream spatial locations, the wetting delay is lower for the tube-type nozzle compared to the sharp edged nozzle. It is observed that the change in Reynolds number and jet diameter does not affect the wetting delay period, even though coolant flow rate and the jet velocity vary to a great extent. At a fixed initial surface temperature, the wetting delay increases towards the higher spatial locations.

Rewetting velocity

The rewetting velocity gives the information how fast the rate of wetting front movement over the heated surface or in short, the speed of the rewetting progress. It gives an indication of how quickly the coolant contributes to effective heat removal from the hot surface. The average quench front velocity (rewetting velocity) between thermocouple locations can be calculated by dividing the axial distance between these locations by the time required for the quench front to move from one location to another. The rewetting velocity decrease with an increase in the initial wall temperature and pressure. Another possible effect of high liquid flow rates is a higher liquid fall over to the region below the quench front, causing higher precursory cooling and increasing the quench front velocity. Increasing the heat conductivity in the axial direction increases the quench front velocity, whereas decreasing the heat conductivity in the radial direction also increases the quench front velocity. Chen investigate transient heat transfer modes and the observation shows that at higher initial wall temperature the rewetting velocity is lower, but with higher flow rate the rewetting velocity increase. Carbajo study the effect of different variables on the rewetting velocity in a light water reactor following a LOCA. It is noted that the rewetting velocity increases as the coolant temperature are reduced and by lowering the clad surface temperature and also inferred that the rewetting velocity could increase with coolant flow. Carbajo and Siegel; Peng and Peterson observed that the wetting velocity for a thin liquid film flowing on a flat surface is reduced for higher surface temperature. However, the velocity increases when the liquid film becomes thicker. Conducted experiments based on jet impingement cooling of a preheated test specimen. Their measurements also reveal strong effects of the initial test specimen temperature and the flow velocity and sub cooling on the quench front velocity. Increased in sub cooled liquid and flow velocity both act to increase the quench front velocity but it decreases with increasing initial specimen temperature. Conducted an experimental to study the rewetting behavior on a hot vertical annular channel, with a hot inner tube, for bottom flooding and top flow rewetting conditions. Their experiment studies also reveal that for a given initial surface temperature of the tube, the rewetting velocity increases with an increase in flow rate of water and it decreases with an increase in the initial surface temperature for a given water flow rate. Carried an experimental work to study the characteristics of heat transfer and wetting front during quenching high temperature cylindrical block by water jet at atmospheric pressure. The observation indicates that the wetting front hardly goes forward until about 4.2 sec after the jet impingement and is limited in the impinging zone. Carried out an experimental study for water jet impingement quenching of a stainless steel specimen heated to about 900°C. It is found that the wetting front velocity increases with the jet velocity and decreases with increase in sub cooling. The splashed droplet velocity is strongly governed by the jet velocity, while a moderate dependence on jet sub cooling conducted an experiment to study of quenching of a hot vertical tube by sudden introduction of a falling liquid film. To study the effect of this steam counter current flow, experiments were carried out in three stages. In the first stage, the tube was closed from top to force the steam generated to be vented from bottom. In the second stage, both ends of the tube were opened to allow venting of the steam from both ends. In the third stage, the tube was closed at bottom and the steam was vented from top. The results showed that, the rewetting velocity in case of bottom steam venting is higher than that in case of top and bottom steam venting which in turn is higher than that in case of top steam venting. For the three methods of steam venting, the quenching velocity decreases with increasing the initial tube temperature and the inlet liquid temperature and decreasing the liquid flow rate. Observed that the rewetting velocity is the highest with the tube type nozzle compared to the sharp edged nozzle. A rise in the rewetting velocity has been observed with the increase in jet diameter and jet Reynolds number. The rewetting velocity generally reduces with the rise in surface initial temperature. Agrawal and Sahu, present the experimental study on the rewetting behavior of a hot vertical stainless steel foil by a circular impinging liquid jet. The rewetting velocity varies within 2.0-20.0 cm/sec, which increase with coolant flow rate and decrease with increase in initial surface temperature. The increase of quenching velocity for nano fluids is attributed to rupture of vapor blanket/film due to turbulence enhancement. Manish Kumar Agrawal and SK Sahu, analyzed of multi region conduction controlled rewetting of a hot surface with precursory cooling by variation integral method. It is observed that at higher coolant flow rate, the wet front velocity is higher and it is necessary to include the precursory cooling in the model. An experimental and theoretical have been conducted by many researchers to understand and elaborate the rewetting by falling film boiling on a heated vertical channel. Some of the examples are Yamanouchi and Yoshioka and Hasegawa studied the rewetting by a falling film of water introduced onto the surface relevant to Boiling Water Reactors (BWRs) cooling. The objective has been to study the mechanism of flow and heat transfer regimes during falling film boiling. In BWRs, the ECCS injects water through the top of the core *via* sprays. Figure 2 shows a typical boiling situation during top flooding. In the wet region behind the edge of the liquid film, heat is removed from the surface by nucleate boiling. In left represent the flow rewetting behavior with higher flow condition. Similarly for low flow rate presented in (right). The effect of low to moderate flow rates at the same pressure, inlet sub cooling and power but at different mass fluxes, varying from 50-201 kg/m^2s, indicate that the wall temperatures decrease with an increasing inlet flow rate. The convective cooling is shown by the cool down rate before arrival of the quench front and the quench time.

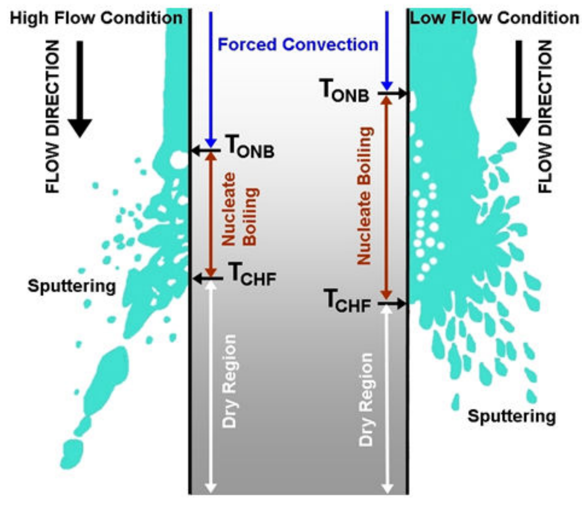

Figure 2: Schematic of the flow pattern in falling film (rewetting process).

In a hypothetical concept of LOCA, the initial fuel rods temperature is much greater than the rewetting temperature. It is characterized by the formation of a wet patch on the hot surface which eventually develops into a moving quench front. The spots where bubbles originate become more numerous closer to the wet front. At the wet front, the wall temperature approaches the critical heat flux temperature. The bubbles are so numerous that they interfere with each other and disrupt the edge of the liquid film. The lateral force associated with nucleation reaches a maximum at the critical heat flux, causing the sputtering of droplets and the shearing of the film from the hot surface. Once the falling film is displaced from the surface, it does not return since the only force acting on the liquid is gravity. The critical heat flux temperature is also known as the sputtering temperature, which clearly characterizes the physical phenomenon of liquid film breakdown associated with top re-flooding. As the quench front progresses along the flow direction, it removes heat from the hot surface by several heat transfer mechanisms such as axial conduction and radial convection and radiation to the coolant. Under low quality, the flow boiling Critical Heat Flux (CHF) decreases significantly with the increased pressure and increases evidently with the augment of mass flux. The CHF related to the inlet enthalpy when the inlet insufficient enthalpy is relatively small and is unaffected by the inlet enthalpy at larger inlet insufficient enthalpy conditions. With increased flow quality, the effects of inlet enthalpy on the calculated CHF get smaller and smaller. Kim observation results for the liquid vapour phase distribution on a boiling surface showed the formation, coalescence and dynamic behaviours of dry spots on a boiling surface and as the surface heat flux increased, the frequency and density of the dry spots significantly increased. Intensive nucleation behaviour near the triple contact line of a dry spot interrupting the wetting of the liquid was observed at a high heat flux. The liquid vapour phase distribution and the temperature evolution of the dry spot area indicated the existence of an irreversible dry spot, which leads to surface overheating and consequent CHF triggering by rapid spreading on a boiling surface. Deng revealed that the porous structures with reentrant cavities presented a significant reduction of wall superheat for the Onset of Nucleate Boiling (ONB) conducted an experiment to investigate the boiling mode transition of subcooled water on a vertical flat surface during quenching process. It was observed that as the quenching process began, the nucleation was initiated within a short time and the surface temperature only slowly varied with low heat flux. The outbreak transition boiling with extremely unstable bubbles occurred just after initial nucleation and its heat flux almost linearly increased investigate the heat transfer on 2024 aluminum alloy thin sheets by water spray quenching. The results indicate that there exists a film boiling regime and Leiden frost point when water temperature is 70°C. The critical heat flux first increases and then decreases with increasing nozzle pressure. The critical heat flux decreases when water temperature increases from 25°C to 60°C. However, the critical heat flux increases when water temperature varies from 60°C to 70°C have studied of saturated pool boiling from downward facing structured surfaces. The results indicated that the CHF increases with the increased inclination angle. Comparing with the plain surface, 61e91% higher CHF increase was achieved on the interconnected-grooves surface with quadrilateral array cavities and more than 102% CHF increase was obtained on the interconnected grooves surface with triangular array cavities. Liu performed a numerical simulation to investigate the sub cooled boiling flow in axisymmetric channels using the two phase particle model. The heat transfer performance of the channel with thickness of 0.225 mm fouling deposit layer is 5 times larger than that with thickness of 1.55 mm fouling deposit layer. It is also found that the inlet velocity has significant impact on the boiling and total pressure drops along the channel. Gao investigated on onset of significant void during water sub cooled flow boiling. The simulation results show that the relative enthalpy of the flow at onset of significant void decreases with a rise in heat flux and with decrease in mass flux and with increase in pressure. Buczek and Telejko investigated the heat transfer coefficient during quenching with various cooling agents. It is observed that while cooling in the mineral oils examined, an increase of heat transfer coefficient was observed with an increase of quenching temperature, particularly near the peak of heat transfer coefficient versus surface temperature curve. Lee et al. conducted an experiment to investigate the effect of nanofluids on reflood heat transfer in a hot vertical tube. It is observed a more enhanced cooling performance in the case of the nanofluid reflood, instead of water reflood. A more enhanced cooling performance is attributed to a high wettability of a thin layer formed on a heating surface by a deposition of nanoparticles. Lee investigate the effect of 35‰ sea salt solution on reflood heat transfer in a long vertical tube (1600 mm in the heating length), quenching experiments were conducted. It was observed amore enhanced cooling performance in the case of the sea salt solution reflood. Consequently, the cooling performance is enhanced more than nearly 10 s for sea salt solution. The cause of the cooling performance enhancement for the sea salt solution is not related to the enhanced wettability of the liquid film on the heater surface due to the deposition of sea salts but the top quenching by earlier condensation of vapor during sea salt solution reload investigate forced convection boiling overwatering a 24 long full scale helically coiled steam generator tube, prototypical of the steam generators with in tube boiling used in small modular nuclear reactor systems. The heat transfer coefficient was found to depend on the mass flux and on the heat flux, indicating that both nucleate boiling and convection are contributing to the heat transfer process study the process of boiling heat transfer during rewetting of a vertical tube by alumina nanofluid. It is observed that rewetting in nanofluids takes place faster than water. Rewetting in general, depends on coolant inlet velocity, initial wall temperature and axial location of the tube from the inlet. For nanofluids, it also depends on the concentration of nanoparticles. Suleiman et al. investigate the heat transfer characteristics in saturated pool boiling of water based nanofluids. It was found that the particle dispersion condition has no noticeable influence on the heat transfer characteristics. In particular, it was found that the wall superheat likely to increase significantly when the nanoparticle layer formed on the heated surface is partially detached. Wang and Su have studied the saturated flow boiling heat transfer of gama Al_2O_3/H_2O nanofluids with 20 nm diameter and 0.1%, 0.5% volume concentration in a vertical tube. The influences of such important parameters shows that the nusselt number of nanofluid flow boiling increases with increasing the surface heat flux, the volume concentration of nanoparticle and pressure. This is one of the effective cooling options over the past few years due to rapid cooling and better control of high temperatures. The complex mechanism of flow boiling heat transfer during jet impingement cooling is not been well understood. Several experimental and analytical investigations have been conducted to understand and elaborate the film boiling heat transfer on high temperature flat plates with a focus on the jet stagnation zone. It is understood that when the liquid jet impinges on the hot solid surface, the entire hot surface does not wet immediately. The liquid splashed out from the local impinged region. In the initial period during quenching, vapor film is formed in plate surface and cooling rate is very slow. Because the thermal resistance of vapor film is large and heat conductivity is very poor, the exchange of the heat flux between the plate and quenching water and surface heat transfer coefficients are very small, with an increase in quenching time, the vapor film is cracked progressively. And cooling rate is rapidly increased. The exchange of heat flux between plate and quenching water is also rapidly increased. Therefore, the surface heat transfer coefficient rises. The physical phenomena in Jet impingement rewetting. The surface temperature drops to a certain value and then the liquid is allowed to move over the hot surface. The immediate cooling at the stagnation region is attributed to be the higher heat transfer rate in this area (Figure 3).

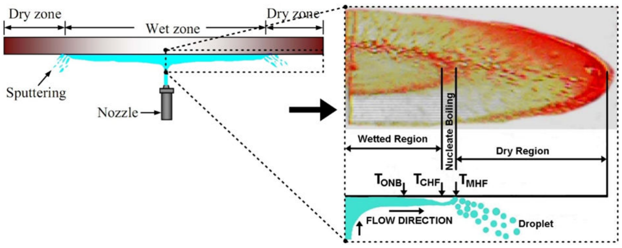

Figure 3: Schematic of the flow pattern in Jet impingement (rewetting process).

During the quench, the flow situation at the particular time, for example, is observed, where the wetting front spreads towards the circumference with time. From the image in we can recognize three different regimes in the flow situation the first is no splashed droplets, the second is splashed droplets generated by strong vapor ejection and the third is a disappearance of the droplets that is the apparently dry area. The boundaries of the three regimes can be identified at the locations of TMHF and TCHF based on the observation. The position of TMHF can be called the wetting front where the temperature of the hot surface drops drastically and this is the regime of heat transfer changes from film to transition boiling. In the region between TMHF and TCHF, the heat transfer changes from film boiling to nucleate boiling that is the region correspond to transition boiling. Islam conducted an experiment to understand the phenomena that happen just after a sub cooled free surface circular water jet impinges on a high temperature surface. A 2 mm water jet of 5-80 K sub cooling and 3-15 m/s velocity was impinged on the flat surface of a cylindrical steel/brass block that was preheated to 500°C-600°C. It is found that for a certain period of time the surface temperature remains well above the thermodynamic limiting temperature that allows stable solid liquid contact Karwa and Stephan investigate free surface jet impingement quenching process. This study presents a systematic methodology for the measurement and estimation of the temporospatial variation of heat transfer on the impingement surface during jet impingement cooling of extremely hot steel plate. The effect of jet impingement velocity and sub-cooling variations from 2.5 to 10 m/s and 60 to 87 K, respectively, on the temporospatial heat transfer variation on the impingement surface is reported. A gradually growing circular wetted region, with its periphery named as the wetting front, forms soon after the cooling starts but its velocity decreases as it grows in diameter. A local maximum in the surface heat flux closely follows the wetting front, with the local maximum heat flux reducing with distance from the stagnation point. The wetting front velocity and local maximum heat flux increase with both the jet velocity and sub cooling. The enhancement in the local film velocity and sub cooling result in a strong suppression of boiling activity and, resultantly, high heat transfer rates at plate surface temperatures in much excess of the critical temperature of the coolant is achieved. Kang investigate the combined effects of an inclination angle and the heat flux of a lower tube on pool boiling heat transfer of a tube bundle. The results reveled that an increase of the heat flux of the lower tube and the decrease of the inclination angle increases the heat transfer coefficient of the upper tube. The increase of the heat transfer coefficient is clearly observed when the inclination angle is less than 30° and the heat flux of the lower tube is greater than that of the upper tube. Lee have conducted numerical simulation to study the flow and thermal characteristics associated with the quenching process, which includes film boiling in the fluid region as well as transient conduction in the solid region, direct numerical simulation is performed for quenching of a hot plate in liquid jet impingement. The computations demonstrate that the boiling curve of wall heat flux versus temperature does not depend on the transient or steady state heating conditions have investigated latent heat model of a medium plate in case of jet quenching. The results showed that the average cooling rate of steel plate decreases by about 3.39°C/s when considering phase transformation latent heat. The temperature rises near surface at one quarter of thickness and the center were about 95°C, 118°C and 127°C respectively. Toghraie have conducted a numerical method for simulation of flow boiling through sub cooled jet on a hot surface with 800°C. The results of this study show that by increasing the velocity of fluid jet of water, convective heat transfer coefficient at stagnation point increases. Moreover, by decreasing the temperature of the fluid jet, convective heat transfer coefficient increases.

Closer and direction for future work

India is presently at advanced stage in the design of an Advanced Heavy Water Reactor (AHWR) which utilizes thorium as fuel. Thorium is 3-4 times more abundant worldwide than uranium. The use of thorium assumes greater significance in India's context, as our uranium resources are limited and our thorium resources are vast. The thorium fuel cycle technologies that are being developed for AHWR will be useful for the large scale thorium utilization in the third stage of Indian nuclear power programme. Since 2008, Candu Energy of Canada and China national nuclear corporation are co-operating in the development of thorium and recycled uranium as alternative fuels for new CANDU reactors. In India, during mid 2010, a pre licensing safety appraisal of the planned experimental thorium-fuelled 300 MW (e) AHWR was completed by the Atomic Energy Regulatory Board. The site-selection process started in 2011; the reactor is expected to become operational by 2020. However, full commercialization of the AHWR is not expected before 2030. The AHWR is a boiling light water cooled heavy water moderated reactor where the heat is removed through natural convection.

With regard to the researcher's problems during the study of the characteristics of rewetting phenomena from the above mentioned literature review, the following statement and comments are drawn:

- Most of the researchers had faced difficulties in tracking rewetting process as the quenching process involves many sub processes which themselves are complicated. Even those who have observed this phenomenon could not record it accurately since the quench front moves rapidly within very short time, which is in fractions of a second.
- Most of the researchers have conducted experiments only for the jet stagnation zone. Some other have conducted experiments for the falling film in single rod. This has not yet brought any understanding for radial jet impingement in vertical rod bundle.

Indian innovative reactor 'AHWR' is a pressure tube type natural circulation based boiling water reactor that is designed to meet such requirements, which essentially reflect the needs of next generation reactors. The reactor employs various passive features to prevent and mitigate accidental conditions, like a slightly negative void reactivity coefficient, passive poison injection to scram the reactor in event of failure of the wired shut down systems, a large elevated pool of water as a heat sink inside the containment, passive decay heat removal based on natural circulation and passive valves, passive ECC injection, etc. It is designed to meet the fundamental safety requirements of safe shutdown, safe decay heat removal and confinement of activity with no impact in public domain and hence, no need for emergency planning under all conceivable scenarios. The radial jet impingement is uniquely designed in AHWR fuel cluster for cooling down the reactor during LOCA. The rewetting phenomena in this complicated fuel cluster have not yet been properly workout. One of the major technological issues is premature dry out induced by the two phase flow instability in the fuel cluster core. It is found that the various passive systems incorporated enable the reactor to tolerate the postulated accident conditions without causing severe plant conditions and core degradation. Experimental studies of this phenomenon are also very costly. Nowadays, it becomes possible to switch to new generation of computational tools in order to get better realistic simulations of complex phenomena and transients. Therefore, approaching CFD analysis on this complexity may prove to be very good for better insight in the phenomena. The rewetting behavior is more or less linearly dependent on the operating conditions, but much effectively response is observed with design parameters. In the present observation, it is very difficult to give a comment on the performance of the rewetting inside the rod bundle, as the flow is irregular and always distorted throughout flow process in the rod bundle. It gives different information to one another location for each position of the rod bundled.

Conclusion

The only valuable information drawn from overall achievement from this present investigation is the following; the rewetting performance can be improved significantly with the jet direction, with proper jet diameter and certain maintaining on the liquid sub cooling and flow conditions depending on the initial wall temperature. Beside all the above mention criteria the following points also affect the rewetting phenomena; material and thickness and the surface roughness of the fuel clad. A few pointed of future work are depicted here which exclude the fundamental accomplishments from the present study;

- Nucleate boiling; detachment and attachment of nucleate bubbles. The dynamics of vapour bubbles formed on a heated surface placed in a pool of liquid or subjected to forced flow has been studied extensively in the past. Bubble dynamics includes bubble growth, merger and departure processes. Bubble induced vibration has become vital in recent investigation and advancement in the area of multiphase boiling. The past report motivates to study the influence of bubble dynamics on the wall heat transfer, the partitioning of energy into vapour and liquid phases and the development of void profile during flow boiling. The rewetting phenomenon can be understood with the help of proper and detailed understanding of vapour bubble formation, growth, collapse and interaction with the surface.
- Fluid types; adding nanoparticles. The effect of nanoparticles on the cooling performance of the Inconel 600 cylindrical rod during quenching have observed the maximum cooling rate of Silicon Carbide (SIC) nan fluid (230°C/s) is faster than pure water (218°C/s). The quenching behaviour of the Nano fluids, some nanoparticles deposit on the surface of the rod, which results in much higher quenching rate in subsequent tests with the same rod. The deposition of nanoparticles changes the surface wettability, but it also causes capillary wicking on a porous surface, whereby the supplied liquid effectively delays the irreversible growth of a dry patch. It is noted that the more detailed investigation should be done in associating with the rewetting behavior.

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