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The Effects of Refolding and Rewetting of Vertical Nuclear Fuel Bundle with Jet Impingements in Nuclear Reactors: A Review

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Abstract—*Rewetting is very important content with thermal control for the safety of nuclear reactors during Loss of Coolant Accident (LOCA), also in manufacturing industries for controlling high temperature, and in micro-electric cooling for electronic systems thermal control. The limiting factor in heat removal in engineering systems involving liquid heat transfer is the boiling crisis. The boiling crisis is especially important in the field of nuclear engineering, as it is one of the main limits on the power extracted per unit volume for both Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR)[1]. Consequently, accurate knowledge of the rewetting is necessary for accurate and enhanced control of the quenching process. The boiling heat transfer regime plays an important role in rapid cooling applications. However, because of its complex and unsteady behavior, it has been historically the least studied. Due to increasing demand for the utility of rewetting in industry, researchers and scientists have carried out with analysis and experiments to study the rewetting phenomena. The following section reports the historical observation on the reflooding and rewetting mechanism. The motivational research gap from the present survey is also included in this chapter.*

Keywords: *Heat treatment. nuclear reactor, reflooding, rewetting, nuclear reactors.*

1. INTRODUCTION:

1.1 Literature review on reflooding:

In water cooled nuclear reactors, rapid heating of the fuel channels occurs during LOCA. The historical failure worldwide, of a nuclear reactor in a mode of LOCA is described Fig. II.A (Appendix II). For preventing the fuel element overheating from reaching a metallurgical prohibitive temperature, an Emergency Core Cooling System (ECCS) is activated. 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). In the recent development of ECCS system inn water based nuclear reactor it has been designed with radial jet impingement [2]. The top flooding and radial jet have been extensively surveyed for as the present work is concerned. The hypothetical concept of coolant flow behavior in the rod bundle of AHWR could be the combined effect 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 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 are much different from the annular or slug regimes[3]. Therefore, a brief history of film falling and jet impingement is discussed in the following section.

1.1. Top Flooding

An experimental and theoretical study has 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 [4], and Yoshioka and Hasegawa [5] studied the rewetting by a falling film of water introduced onto the surface relevant to boiling water reactors (BWRs) cooling. The critical heat flux temperature is also known as the sputtering temperature [6], 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 [9]. The CHF is related to the inlet enthalpy when the inlet insufficient enthalpy. With increased flow quality, the effects of inlet enthalpy on the calculated CHF get smaller and smaller[10]. Kim et al. [11] observed results for the liquid–vapor phase distribution on a boiling surface which showed the formation, coalescence, and dynamic behaviors of dry spots on a boiling surface, and as the surface heat flux increased, the frequency and density of the dry spots significantly increased

Deng et al.[12], revealed that the porous structures with reentrant cavities presented a significant reduction of wall superheat for the onset of nucleate boiling (ONB). Lu et al.[13], conducted an experiment to investigate the boiling mode transition of subcooled water on a vertical flat surface during quenching process. Guo et al. [14],[15], has investigated the heat transfer on 2024 aluminum alloy thin sheets by water spray quenching. Zhong et al. [16], has studied about saturated pool boiling from downward facing structured surfaces. The results indicate that the CHF increases with the increased inclination angle. Liu et al.[17], performed a numerical simulation to investigate the sub-cooled boiling flow in axisymmetric channels using the two-phase particle model. Gao et al.[18] investigated on onset of significant void during water subcooled flow boiling. Buczek and Telejko [19], investigated the heat transfer coefficient during quenching with various cooling agents. Lee et al. [20], conducted an experiment to investigate the effect of nanofluids on reflood heat transfer in a hot vertical tube. Lee et al.[21], investigated the effect of 35‰ sea salt solution on reflood heat transfer in a long vertical tube (1600 mm in the heating length), and quenching experiments were conducted. Santini et al.[22], investigated forced convection boiling of water in a 24 m long full-scale helically coiled steam generator tube, prototypical of the steam generators with in-tube boiling used in small modular nuclear reactor systems. Paul et al.[23], has studied 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. Sulaiman et al.[24], investigated the heat transfer characteristics in saturated pool boiling of water-based nanofluids. Wang and Su [25] 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.

1.2. Jet Impingement:

This is one of the effective cooling options over the past few years due to rapid cooling and better control of high temperatures. Several experiments and analytical investigations has been conducted to understand and elaborate the film boiling heat transfer on high temperature flat plates with a focus on the jet stagnation zone. Some of the examples are, Liu and Wang [26], Hall et al. [27], Hammad et al. [28], Mozumder et al. [29], and C. Agarwal et al.[30],[31],[32]. 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 [33]. Islam et al.[35], conducted an experiment to understand the phenomena that happen just after a subcooled 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 500–600^{o}C. It is found that for a specific period, the surface temperature remains well above the thermodynamic limiting temperature that allows stable solid–liquid contact. Karwa and Stephan [36],[37], has investigated free-surface jet impingement quenching process. This study presents a systematic methodology for the measurement and estimation of the temporo-spatial variation of heat transfer on the impingement surface during jet impingement cooling of extremely hot steel plate. Kang [38] investigated the combined effects of an inclination angle and the heat flux of a lower tube on pool boiling heat transfer of a tube bundle. Lee et al. [39], has 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. Fu et al.[40], has investigated latent heat model of a medium plate in case of jet quenching. Toghraie [41], has 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.

2. LITERATURE ON REWETTING:

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 [42]. The terms quenching, sputtering, minimum-film-boiling point (MFB), return to nucleate boiling and Leidenfrost phenomenon is often used interchangeably to refer to various forms of rewetting [43]. Hsu et al.[44], has 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. Xu et al.[45], has studied the influence of pressure and surface roughness on the heat transfer efficiency during water spray quenching of 6082 aluminum alloy. Su et al.[46], has studied the heat transfer performance of an oscillating heat pipe (OHP) with self-rewetting nanofluid. Hu et al.[47],[48], carried out boiling experiment to clarify the fundamental heat transfer characteristic and heat transfer enhancement mechanism of pool boiling with Self-rewetting fluid (SRWF). Kang et al. [49] showed that through high speed visualization, it is observed that intermittent wetting during FBHT resulted in an unstable liquid–vapor interface in case of the CWS. Kim et al. [50], has studied a heat flux partitioning analysis of nucleate pool boiling on micro structured surface through infrared visualization technique. Yagov et al. [51], conducted an experiment for film boiling of subcooled liquids. Kozlov and Kebler [52] studied an influence on liquid quenching by surface structuring. It was found that the purposefully structured surface can affect quenching kinetic considerably. Chung et al.[53], investigated the heat transfer and boiling characteristics for the downward facing wall heating. Sahu et al.[54], investigated the effect of the several coolant injection system. Patil et al.[55], carried out an experimental investigation of rewetting of AHWR rod bundle with radial jets. Mithilsh et al.[56], [57],[58] studied influence of rewetting of AHWR fuel bundle. 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[59]. Extensive studies on the rewetting of hot surfaces have been carried out from the earlier work.

2.1 Rewetting temperature:

Rewetting temperature is one of the most critical term and understanding the behavior of this term is required in engineering and scientific fields for the safety analysis during boiling crisis in light water reactors (Pressurized Water and Boiling Water Reactors). Hall et al. [27],[60] 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. [32],[61],[62] conducted the experiments for the effect of jet diameters in the range of 2.5–4.8 mm. 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. Further, by Agarwal et al. [63] investigation has been performed to study the rewetting behavior for three different initial surface temperatures viz. 255, 355, 565°C. The rewetting temperature for the entire range of measured spatial location increases with the rise in surface initial temperature. Further, Agarwal et al. [30], 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. Fan et al.[76], has studied the effects of surface wettability, from super hydrophilic to super hydrophobic, on transient pool boiling of water under atmospheric pressure. It was experimentally examined by means of the quenching method with hot stainless steel spheres.

2.2 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 decreases[8]. The wetting delay or quenching time does not appear to be directly connected with the time to reflood. As a consequence, quenching time is not connected with the peak cladding temperatures but only with the reflood flow rate: lower reflood rates clearly lead to longer quenching times[77]. Piggott et al. [64], observed that the delay time is independent of jet size for a particular set. The wetting delay is found to be vary 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 has little effect. Mozumder et al. [29], investigated 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 to 400ºC. Results show that the wetting delay increases with an increase in initial temperature. Hossain and Hossain [65] 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. [32],[30],[61],[63] observed that the wetting delay period increases for the locations away from the stagnation point.

2.3 Rewetting Velocity:

The rewetting velocity gives the information about how fast the rate of wetting front movement over the heated surface or in short, the speed of the rewetting progress. 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[8]. The rewetting velocity decreases with an increase in the initial wall temperature and pressure. Another possible effect of high liquid flow-rates is a higher liquid fall over 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[78]. Chen et al. [66], has investigated 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 increases. Carbajo [67], has studied the effect of different variables on the rewetting velocity in a light water reactor following a LOCA.. Carbajo and Siegel [68]; Peng and Peterson [69], 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. Filipovic et al. [70], conducted experiments based on jet impingement cooling of a preheated test specimen.. Saxena et al. [71], 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. Hammad et al. [28], 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.. Karwa et al. [72], carried out an experimental study for water jet impingement quenching of a stainless-steel specimen heated to about 900°C. Nada et al.[79][80], conducted an experiment to study of quenching of a hot vertical tube by sudden introduction of a falling liquid film. Agarwal et al. [30], 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 [31],[32],[62]. The rewetting velocity generally reduces with the rise in surface initial temperature [63]. Agrawal and Sahu [73], have presented the experimental study on the rewetting behavior of a hot vertical stainless steel foil by a circular impinging liquid jet. The increase of quenching velocity for nanofluids is attributed to rupture of vapor blanket/film due to turbulence enhancement[20]. Manish Kumar Agrawal and S.K. Sahu[81], analyzed the 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.

3. CONCLUSION

With regards to the researcher's problems during the study of the characteristics of rewetting phenomena from the above 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 others have conducted experiments for the falling film in single rod [57],[56]. This has not yet brought any understanding for radial jet impingement in vertical rod bundle.

4. SCOPE FOR FURTHER RESEARCH:

Indian innovative reactor 'AHWR' is a pressure-tube type natural circulation based boiling water reactor that is designed to meet such requirements, which essentially reflects 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 the 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[82]. 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 has not yet been properly worked out. 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. [74]. Experimental studies of this phenomenon are also very costly. Nowadays, it becomes possible to switch to new generation of computational tools 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.

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