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Review of Enhancement of Thermal limit of Water-Cooled Nuclear Energy Conversion Applications through Nanotechnology

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ABSTRACT

A number of water-cooled reactor designs consist of safety and improved economics are being proposed by nuclear power industries all around the world along with the objective to propose solutions to the future energy supply shortfall. Thermal-hydraulics [1] could be considered as a key scientific subject in the development of enhanced reactor systems. The change of phase by boiling and condensation in the reverse process is most efficient heat transport mechanism that pertains large heat fluxes with relatively small driving temperature differences. This manner of heat transfer can be used in a wide spectrum of nuclear systems, and thus it is necessary to determine the thermal limit of water-cooled nuclear energy conversion for both economic and safety point of view. Such applications are being improved with the introduction of new technologies such as nanotechnology. Here, the efforts are made to investigate newly-introduced nanotechnologies relevant to boiling and condensation in general engineering applications.

Keywords: *Thermal hydraulics, phase change, Boiling heat transfer, critical heat flux, Quenching efficiency.*

1 INTRODUCTION

Conversion of energy has a major impact in the development of modern society following the Industrial Revolution. This field of engineering is related to the transformation of energy from sources such as fossil fuels and nuclear fuels and the sun into useful forms such as thermal, mechanical, and electrical energy. Modern Engineers face numerous choices and challenges related to engineering owing to the global energy crisis and climate change, especially with respect to extreme demand in terms of economics and environmental safety in energy conversion [1]. The existing demand is directly connected to the efficiency of energy conversion, which is a measure of the quality of an operation or of the characteristics of a device. Generally, mass production of the most fundamentally essential form of energy, electricity, depends on power plants and the concerned factors are directly linked with thermodynamics, fluid mechanics, and heat transfer [2].

The necessity of the thermal-hydraulic phenomena with phase change (from liquid to vapor) of a coolant in nuclear engineering comes from the fact that many reactors use a liquid coolant that is subjected to high heat fluxes [3]. Change of phase by boiling or evaporation or condensation in the reverse process is a highly efficient heat transport mechanism, which accommodates large heat fluxes with relatively small driving temperature differences. Such applications are being advanced with the introduction of new technologies such as nanotechnology. At present, we made our research that used nanotechnologies for boiling and condensation. It should also be tried to find out the connection between such innovative recent advancements and nuclear applications in terms of advanced nuclear thermal-hydraulics.

2. PROCESSES REGARDING CHANGE OF PHASE IN NUCLEAR SYSTEMS: BOILING AND CONDENSATION

Boiling and condensation are processes that are mostly exist at a solid-liquid interface. Latent heat is the governing effect related with the phase change. The change of phase from a liquid to vapor due to boiling (evaporation within a continuous liquid phase) is governed by heat transfer from the solid surface whereas in condensation process, gaseous phase substance changes into a liquid phase, and can be taken as the inverse of evaporation. It is well known that, due to combined latent heat and buoyancy-driven natural convection effects, boiling and condensation heat transfer coefficients are much larger than those of single phase convection heat transfer without phase change [4]. Hence it may be stated that, thermal power plants, including nuclear power plants adopt such higher heat transfer modes for better performance. These features play important roles in nuclear power plants (NPPs), both under normal operation and abnormal operating conditions.

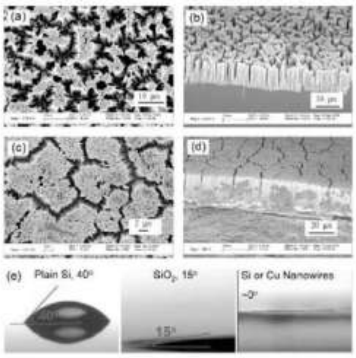
In a pressurized water reactor (PWR), boiling is utilized in a steam generator whereas local boiling at the fuel surface in the nuclear core can be permitted at high power for improvement of heat transfer [5]. During normal operation, the high pressure secondary coolant, that is, water, is evaporated at the steam generator and expands in turbines to produce boundary work. The final exhausted steam goes to a condenser and rejects internal energy and condenses to change once again into water. In Pressurized water reactor (PWR), primary loop consist of pressurizer, where primary coolant water evaporates by electric heaters and condenses by a subcooled water spray.

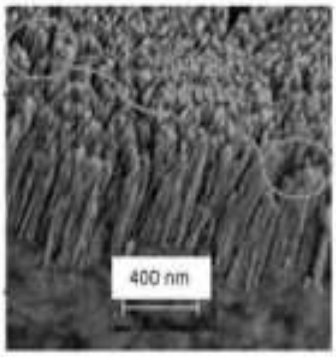
3 INNOVATION IN BOILING AND CONDENSATION USING NANOTECHNOLOGY

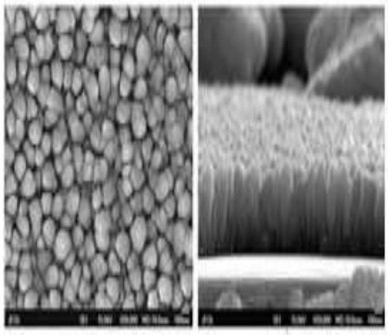
A lot of work to introduce nanotechnology to boiling and condensation have been boosted by new developments in nonmaterial's consist of unique properties arising from their nanoscale dimensions [1].

3.1 INNOVATION IN BOILING SYSTEMS BY SURFACE MODIFICATION TECHNOLOGY (NANOTECHNOLOGY)

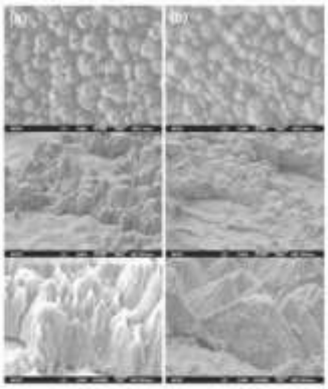
To enhance boiling heat transfer/ critical heat flux, surface modification technology normally has been considered. By this approach, the heating surface conditions related to boiling mechanisms or key parameters, are modified. A lot of research related to surface modification has conventionally focused on increasing the surface roughness via coating with appropriate microstructures [6]. Such kind of enhancements generally increases the surface roughness and the number of micro-cavities, thus including the nucleation site density, resulting in improvement of boiling heat transfer (BHT). On the other side, in contrast to critical heat flux, the modification can manage the contact angle of the liquid on the surface, resulting in changed surface wettability. Such surface parameters are in charge of the capillary effect of the surface micro-structure, resulting in a porous structure that will extend the boiling regime and delay CHF through enhanced liquid spreading over the heated area. The use of nanotechnology for surface modification can be subdivided into the five catagories: (a) deposition of nanorod, (b) nanowires, (c) deposition of nanomaterial, (d) coarse nano-/micro-structures, and (e) nanoparticle thin film coatings. The investigated outcomes of the surface images of which by several authors [6-10] are shown in Figure







Chen et al [6] **Li et al. [7]** **Sesen et al.[8]**



Ahn et al.[9] **Ahn et al.[10]**

Figure 01 Nanostructures for (Thermal) Boiling enhancements [6-10]

Li et al [7] made their study on nucleate boiling and focused on nanoscale gas cavities as nucleation sites are formed on Copper nanorods. Nanorods were deposited on a polished Cu substrate by an electron-beam evaporator. With the help of nanosurfaces, they obtained an estimated 30 times enhancement in the density of active bubble nucleation sites, that leads to a higher boiling heat transfer coefficient. Smaller bubble departure diameters and higher release frequencies related to the relatively small size of the microcavities are their further observations.

3.2 INNOVATION IN BOILING SYSTEMS BY NANOFLUID TECHNOLOGY (FLUID-MODIFICATION TECHNOLOGY)

In past few years, fluids that contain suspensions of nanometer-sized particles (termed nanofluids as coined by S. Choi (1995, Argonne National lab, USA: dilute liquid suspensions of nanoparticulate solids including particles, nanofibers, and nanotubes [11])) have been greatly researched due to their enhanced thermal properties over the base fluids. Conventional heat transfer fluids, such as water and refrigerants, are inherently poor heat transfer fluids due to the fundamental limit in thermal conductivity of conventional fluids. Higher thermal conductivity small solid particles (nanoparticles) with size below 100 nm can suspend in aqueous solutions of surfactants or solvents without damaging the structure of heat transfer systems (i.e., there is no abrasion or clogging). Colloidal suspensions have shown fascinating thermal performances, especially regarding the following four points: (1) increased thermal conductivity (~150%); (2) increased single-phase heat transfer coefficient (~60%); (3) increased critical heat flux with extended nucleate boiling regime (~200%) and (4) improved quenching efficiency. In addition, nanofluids exhibit a very significant enhancement (up to +200%) of the boiling Critical Heat Flux (CHF) at low nanoparticle concentration (the CHF is the limit of the most efficient heat transfer regime or nucleate boiling or the indirect limit of the above-mentioned attainable energy-source temperature) [12, 13]. On the basis of above mentioned factors, nanofluids are very attractive heat transfer fluids with regard to many applications.

In particular, potential nuclear safety systems adopting nanofluid coolants in current water-cooled reactors might include engineered features such as an Emergency Core Cooling System (ECCS), External Reactor Vessel Cooling System (ERVCS), and In-Vessel/Ex-Vessel Core Catcher Systems. Also, the application of nanofluids can be expanded into both PWRs and BWRs [13]. For boiling heat transfer enhancement, Wen and Ding [14] performed pool boiling heat transfer using alumina nanofluids with primary particle size of 10-50 nm. The results showed that boiling heat transfer was enhanced by as much as roughly 40% at 1.25 w%.

One of the most interesting characteristics of nanofluids is their capability to significantly enhance the Critical Heat Flux (CHF) [15, 16]. Since the CHF is the upper limits of phase-change nucleate boiling heat transfer, the most efficient heat transfer mode, such enhancement provides potential for major performance improvement in many practical applications related to thermal management.

Boiling phenomenon also characterized by quenching process that based on rapid cooling of a liquid on a hot surface. In particular, when a loss of coolant accident occurs in NPPs, the fuel can reach very high temperatures, threatening the integrity of the fuel and cladding. The emergency core cooling system (ECCS), which injects water into the reactor core, immediately starts to work to decrease the fuel temperature [17-19]. Cooling starts with developing a quench front as the head of liquid advances along with the fuel element. The speed of the quench front, and thus the peak fuel temperature reached during the accident, depends on a combination of factors including nucleate boiling, film boiling, and wetting condition of the fuel surface. It could be assumed that the use of nanofluids potentially could improve the quench front speed and thus enhance the safety of the reactors [17-19]. In fact, the quenching front is governed by the boiling phenomena. Some studies have focused on the effects of nanofluids on quenching. Park et al. [20] carried out quenching experiments with a copper sphere in alumina nanofluids. The concentration of nanoparticles ranged from 5 to 20 vol%. The outcome showed that the film boiling heat transfer coefficient in the nanofluids was lower than that in pure water. Xue et al. [21] performed quenching experiments with a nickel-plated copper sphere in a pool of water-based nanofluids containing carbon nanotubes (CNTs). They found that, as compared to water, an aqueous gum arabic solution has an enhanced critical heat flux, transition boiling, and minimum heat flux point in film boiling and thereby it may be stated that CNT nanofluids have a higher CHF on selected observations.

3.3 ADVANCE NUCLEAR COOLANTS ENRICH WITH NANOFLUID &SAFETY FEATURES

The research over Nanofluid related to CHF enhancement reflects that the use of nanofluids as a nuclear coolant in the primary cooling loop of a light water reactor could improve heat removal from the core in terms of higher DNBR (Departure from Nucleate Boiling Ratio). Along with this CHF enhancement provides a larger safety margin into External Reactor Vessel Cooling for In- Vessel Retention as a severe accident management strategy [22-23]. Recently, Hadad et al. [24] studied the nuclear effects of various nanofluids for theVVER-1000 reactor core. The observations reflect that, for normal operation, where a minor change of K_{eff} is tolerated, Al_2O_3/water is a better nanofluid. However, in transient and accident conditions where retention is the purpose of nanofluid use, Cu/water and ZrO2 nanofluids will depress Keff most. In addition, they showed that Keff is decreased with increasing thickness of the nanoparticle deposition layer on the fuel cladding. Kang et al. [25] suggested a nanofluid-engineered SIT specifically established to meet the design requirements of a safety injection system, as shown in Figure 2.

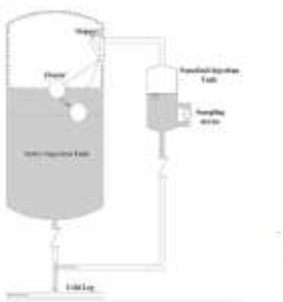


Figure 02: SIT equipped with Nanofluid [25]

3.4 HYDROPHOBIC SURFACE IN CONDENSATION SYSTEMS

Phenomenon of condensation can be divided into several categories depending on the phase contact structure and condensate behavior. Direct-contact condensation [1] refers to condensation of vapor that is in direct contact with a subcooled liquid. Condensation occurs on the wall surface when the surface temperature is below the saturation temperature of adjacent vapor. In initial phase, water droplets nucleate on the cold wall. As the condensation proceeds, these droplets grow and may start rolling down the wall to reproduce a fresh dry surface. Or, these droplets may coalesce to form a condensate film on the wall surface and flow downward as a result of gravity. The first type of condensation is termed dropwise condensation (DWC) while the second one is known as filmwise condensation (FWC). DWC can be visualized on hydrophobic surfaces where the contact angle is much larger than 90 degrees while FWC occurs on hydrophilic surfaces where the contact angle is smaller than 90 degrees. Hydrophobic surfaces have large potential in a wide range of applications. Lotus leaves repel rain drops on their uniformly super hydrophobic surface with the result that water droplets roll off of the leaves [26]. Low surface energy may help reduce frictional head loss of a body moving through water. Hydrophobic surfaces enhance the condensing heat transfer coefficient, and hence it may find various potential applications in NPP design. Textured hydrophobic surface can considered to enhanced heat transfer by achieving drop-wise condensation, upon which condensate droplets are produced and roll down the surface to reproduce a dry surface with the result of which the thermal resistance due to the condensate is minimized. Fabrication of hydrophobic surfaces can be done by various methods. Latest advancements of micro- and nano-size process technologies have made the fabrication of nano-size structures on flat surfaces possible that may used to enhance heat transfer in NPP. Some examples can be, Teflon [27, 28], PFOS (perfluoro-octane sulfonates) [29].

4 FUTURE TRENDS OF HEAT TRANSFER THROUGH NANOFLUIDS

Nanotechnology is the latest technique that needs to be used all over the globe with increasing demand of energy. The challenges of enhancing heat transfer via various advanced boiling and condensation means with nanofluids needs to be expand significantly in the near future to enhance Nuclear Thermal-Hydraulics and Safety features in nuclear power systems, as progress through other small & large scale-based technologies nearly lags pace.

5 CONCLUSION

From the above review it may be concluded that both the performance of Boiling and CHF serves better for nuclear applications. Small modifications in above mechanisms requires enhancing CHF and flowing boiling heat transfer and by the virtue of which in upcoming future, it might possible to sort out the actual challenging situations with complex problems successfully.

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