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Review of applications of Nano Fluids for heat transfer & efficiency of Safety Systems in Nuclear Power Plants

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ABSTRACT

Nano-fluids are a new class of fluids engineered by adding nanoscale particles (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheet, or droplets) in low volumetric fractions to a base fluid in order to enhance or improve their mechanical, optical and thermal properties. The word nano-fluid is developed by Choi et al. [1]. The base fluid can be any liquid such as oil, water, ethylene glycol, or conventional fluid mixtures. These fluids are known for their increased thermo-physical properties as compared to the base fluid and thus can be effectively used as coolant to transfer heat in the core as well as the safety systems of the Power plant. The enhancement of heating or cooling by nano fluids in an industrial process may create a saving in energy, reduce process time, raise thermal rating and lengthen the working life of equipment. Some processes are even affected qualitatively by the action of enhanced heat transfer. The development of high performance thermal systems for heat transfer enhancement has become popular nowadays. A number of work has been carried out to gain an understanding of the heat transfer performance for their practical application to heat transfer enhancement. Thus the advent of high heat flow processes has created significant demand for new technologies to enhance heat transfer.

Keywords: Critical heat flux, Emergency core cooling system, safety injection system, shutdown cooling system, quenching.

I.INTRODUCTION

Colloidal dispersions of nano particles are known as 'nanofluids [2]'. It is important to note that preparation **of nanofl**uids is an important step for investigating nanofluids. Here the methods to prepare nanofluids is discussed briefly Such engineered fluids offer the potential for enhancing heat transfer, particularly boiling heat transfer. Heat transfer characteristics of nanofluids and its applicability to nuclear power systems (i.e., primary coolant, safety systems, and severe accident mitigation strategies) are discussed especially the Critical Heat Flux limit and quenching phenomena. The thermal characteristics of nanofluids have been surveyed.

.It was shown that the nanoparticles can enhance the Critical Heat Flux limit and accelerate quenching heat transfer. These findings can be used in water-cooled nuclear reactors to realize sizable power uprates in the core, thus attaining significant economic gains or improved safety margins. Big attempts have been made to exactly predict thermo physical properties of nanofluids them but large amount of variations were found. There are a number of challenges facing the nanofluids ranging from formulation, practical application to mechanism etc.

The essential requirements that a nano-fluid must fulfill are even and stable suspension, adequate durability, negligible agglomeration of particles, no chemical change of the particles or fluid, etc. In the synthesis of nano-fluids agglomeration is a major problem. There are mainly three techniques used to produce nano-fluids:

- the one-step
- the two-step method and
- chemical reduction method [3].

1.1 ONE STEP METHOD

One-step method is favorable for metallic nanoparticles-since the nanoparticles are dispersed in the base fluid as they are produced, this process helps prevent oxidation of the particles. An advantage of the one step technique is that nanoparticle agglomeration is minimized. The one-step process consists of simultaneously making and dispersing the particles in the fluid [4]. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles are avoided, so the agglomeration of nanoparticles

is minimized, and the stability of fluids is increased. The one-step processes can prepare uniformly dispersed nanoparticles and the particles can be stably suspended in the base fluid.

1.2 TWO STEP METHOD

Two-step method is the most widely used method for preparing nano-fluids. Nanoparticles, nano-fibers, nanotubes, or other nano-materials synthesized in this method are first produced as dry powders by chemical or physical methods. Then, the nano sized powder will be dispersed into a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing and ball milling. Two step method is the most economic method to produce nano-fluids in large scale.

1.3 CHEMICAL REDUCTION METHOD

Chemical reduction method, the reduction of metal salts, is the simplest and most commonly used one step method for metal nanoparticles. The production of nano-sized metal silver particles with different sizes and morphologies using chemical reduction of silver salts has been reported [5, 6]. This method involves reduction of an ionic salt in an appropriate medium in the presence of stabilizing and reducing agents [7]. More over chemical reduction method has been extensively used because of its advantages of yielding nanoparticles without agglomeration, high yield and low preparation cost [8, 9].

II.APPLICATION OF NANOFLUIDS IN HEAT TRANSFER

There are several methods [10] to improve the heat transfer efficiency. Some methods are utilization of extended surfaces, application of vibration to the heat transfer surfaces, and usage of micro channels. Heat transfer efficiency can also be improved by increasing the thermal conductivity of the working fluid. Commonly used

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heat transfer fluids such as water, ethylene glycol, and engine oil have relatively low thermal conductivities, when compared to the thermal conductivity of solids. High thermal conductivity of solids can be used to increase the thermal conductivity of a fluid by adding small solid particles to that fluid. The feasibility of the usage of such suspensions of solid particles with sizes on the order of 2 millimeters or micrometers was previously investigated by several researchers and the following significant drawbacks were observed [11].

1. The particles settle rapidly, forming a layer on the surface and reducing the heat transfer capacity of the fluid.
2. If the circulation rate of the fluid is increased, sedimentation is reduced, but the erosion of the heat transfer devices, pipelines, etc., increases rapidly.
3. The large size of the particles tends to clog the flow channels, particularly if the cooling channels are narrow.
4. The pressure drop in the fluid increases considerably.
5. Finally, conductivity enhancement based on particle concentration is achieved (i.e., the greater the particle volume fraction is, the greater the enhancement—and greater the problems, as stated above).

   Nanofluid is a new kind of heat transfer medium, containing nanoparticles (1–100 nm) which are uniformly and stably distributed in a base fluid [10]. These distributed nanoparticles, generally a metal or metal oxide greatly enhance the thermal conductivity of the nanofluid, increases conduction and convection coefficients, allowing for more heat transfer. Nanofluids have been considered for applications as advanced heat transfer fluids for almost last two decades.

Compared to conventional solid–liquid suspensions for heat transfer intensifications, **nanofluids having properly dispersed nanoparticles possess the following advantages:**

1. High specific surface area and therefore more heat transfer surface between particles and fluids.
2. High dispersion stability with predominant Brownian motion of particles.
3. Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
4. Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization.
5. Adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications [10].

The novel and advanced concepts of nanofluids offer fascinating heat transfer characteristics compared to conventional heat transfer fluids. There are considerable researches on the superior heat transfer properties of nanofluids especially on thermal conductivity and convective heat transfer. Applications of nanofluids in industries such as heat exchanging devices appear promising with these characteristics. Several authors reported that nanofluids can be used in following specific areas[10].

1. Heat-transfer nanofluids.
2. Tribological nanofluids.
3. Surfactant and coating nanofluids,
4. Chemical nanofluids,
5. Process/extraction nanofluids,
6. Environmental (pollution cleaning) nanofluids,
7. Bio- and pharmaceutical-nanofluids,

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8. Medical nanofluids (drug delivery and functional tissue–cell interaction).

III.UNIQUE FEATURES OF NANO FLUIDS

Abnormal enhancement of thermal conductivity: The most important feature observed in nanofluids was an abnormal rise in thermal conductivity, far beyond expectations and much higher than any theory could predict.

Stability: Nanofluids have been reported to be stable over months using a stabilizing agent.

Small concentration and Newtonian behavior: Large enhancement of conductivity was achieved with a very small concentration of particles that completely maintained the Newtonian behavior of the fluid. The rise in viscosity was nominal; hence, pressure drop was increased only marginally.

Particles size dependence: Unlike the situation with microslurries, the enhancement of conductivity was found to depend not only on particle concentration but also on particle size. In general, with decreasing particle size, an increase in enhancement was observed [10, 11].

IV.THERMO PHYSICAL PROPERTIES OF NANOFLUIDS

Thermo physical properties of the nanofluids are quite essential to predict their heat transfer behavior. It is extremely important in the control for the industrial and energy saving perspectives. There is great industrial interest in nanofluids. Nanoparticles have great potential to improve the thermal transport properties compared to conventional particles fluids suspension, millimetre and micrometer sized particles. In the last decade, nanofluids have gained significant attention due to its enhanced thermal properties. A lot of research reflects that thermal conductivity of nanofluids depends on many factors such as particle volume fraction, particle material, particle size, particle shape, base fluid material, and temperature. Amount and types of additives and the acidity of the nanofluid were also shown to be effective in the thermal conductivity enhancement [10].

The transport properties of nanofluid: Dynamic thermal conductivity and viscosity are not only dependent on volume fraction of nanoparticle, also highly dependent on other parameters such as particle shape, size, mixture combinations and slip mechanisms, surfactant, etc. Studies showed that the thermal conductivity as well as viscosity both increases by use of nanofluid compared to base fluid.

4.1. THERMAL CONDUCTIVITY

A wide range of experimental and theoretical studies were conducted to model thermal conductivity of nanofluids. The existing results were generally based on the definition of the effective thermal conductivity of a two-component mixture. The Maxwell model [12] was one the first models proposed for solid–liquid mixture with relatively large particles. It was based on the solution of heat conduction equation through a stationary random suspension of spheres. The effective thermal conductivity (Eq.1) is given by

$$k_{eff} = \{[k_p + 2k_{bf} + 2\phi(k_p - k_{bf})] / [(k_p + 2k_{bf} - \phi(k_p - k_{bf}))]^* k_{bf}\} \quad \ldots\ldots(1)$$

Where, k_p is the thermal conductivity of the particles,

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k_{eff} is the effective thermal conductivity of nano fluid,

k_{bf} is the base fluid thermal conductivity, and

ϕ is the volume fraction of the suspended particles.

Generally thermal conductivity of nanofluids increases with decreasing particle size. This trend is theoretically supported by two mechanisms of thermal conductivity enhancement; Brownian motion of nanoparticles and liquid layering around nanoparticles [13]. But some exceptions also exist that indicate decreasing thermal conductivity with decreasing particle size [14].

4.2 VISCOSITY

Compared with the experimental studies on thermal conductivity of nano fluids, there are limited rheological studies reported in the literature for viscosity. Different models of viscosity have been used by researchers to model the effective viscosity of nanofluid as a function of volume fraction. Einstein [15] determined the effective viscosity of a suspension of spherical solids as a function of volume fraction (volume concentration lower than 5%) using the phenomenological hydrodynamic equation (Equation 2). This equation was expressed by

$$\mu_{eff} = (1+2.5\phi)\mu_{bf} \quad \ldots\ldots(2)$$

Where,

μ_{eff} is the effective viscosity of nanofluid,

μ_{bf} is the base fluid viscosity, and

ϕ is the volume fraction of the suspended particles.

V.INCREASE IN THERMAL CONDUCTIVITY OF NANO FLUIDS AND THEIR APPLICATION TO SAFETY SYSTEMS OF NUCLEAR POWER PLANTS

Choi et al. [1] reported large enhancements in the thermal conductivity of common heat transfer fluids when small amounts of metallic and other nanoparticles were dispersed in these fluids. Several authors [16-22] have also reported large thermal conductivity enhancements in nano-fluids containing metal nanoparticles.

There are two physical phenomena that limit the thermal power of a LWR: (i) Critical Heat Flux (CHF) and (ii) Quenching heat transfer. CHF is the chief limit during a loss of-flow trasient or an overpower transient in which a transition from nucleate boiling to film boiling occur due to either a reduction in the coolant flow or an excursion of the heat flux, respectively. When CHF occurs, the nuclear fuel overheats and can be damaged thereby resulting in fission product release; therefore, limits are imposed on the power of nuclear reactors to prevent the occurrence of CHF. Second, quenching, which refers to the rapid cooling of a very hot object exposed to a cool fluid, occurs in the wake of a loss of-coolant accident, when the emergency core cooling system injects room-temperature water into the core, to reduce the temperature of the fuel that is no longer covered by the primary coolant. The speed at which the quenching process progresses throughout the core determines the maximum fuel temperature attained during the accident, which in turn determines the safety margin to fuel damage. The U.S. Nuclear Regulatory Commission mandates that during these hypothetical accidents the clad temperature remain below a postulated limit (~1200°C), which is ensured by limiting the steady-state reactor power and maximizing the rate of emergency coolant injection. Hence an enhanced CHF and a rapid quenching process are desirable attributes for the nuclear reactor coolant [23].

A **LOCA** is an accident which occurs due to a break in a *reactor coolant system* (RCS) pipeline in a NPP. LOCAs are considered to be serious accidents because of the possibility of core meltdown. As the reactor coolant drains out of the RCS, the temperatures of the nuclear fuel rods increase due to the lack of coolant. Core meltdown may result from the increased temperatures of the fuel rods. An *emergency core cooling system*(ECCS) is one of the engineered safety features and supplies sufficient coolants to a core for maintaining fuel temperatures below its melting point and therefore core meltdown could be avoided in case of a LOCA. An ECCS consists of a safety injection system (SIS) and a shutdown cooling system (SCS). The purpose of the SIS is core heat removal and power decrease via borated water injection following a LOCA.

The colloidal suspensions have substantially shown intriguing thermal performances regarding four points:

(1) Increased thermal conductivity (approx. 150%),

(2) Increased single-phase heat transfer coefficient (approx. 60%),

(3) Increased critical heat flux with extended nucleate boiling regime (approx. 200%), and

(4) Improved quenching efficiency[24].

These properties were expected to be better especially when nano-fluids are employed as coolants in ECCSs, and several applications to light water reactors have been published [25-28].

VI.CURRENT AND FUTURE TRENDS OF HEAT TRANSFER THROUGH NANOFLUIDS

The increases in effective thermal conductivity are important in improving the heat transfer behavior of fluids. A number of other variables also play key roles. For example, the heat transfer coefficient for forced convection in tubes depends on many physical quantities related to the fluid or the geometry of the system through which the fluid is flowing. These quantities include intrinsic properties of the fluid such as its thermal conductivity, specific heat, density, and viscosity, along with extrinsic system parameters such as tube diameter and length and average fluid velocity. Therefore, it is essential to measure the heat transfer performance of nanofluids directly under flow conditions. A lot of studies reflects that nanofluids have not only better heat conductivity but also greater convective heat transfer capability than that of base fluids.

VII.CONCLUSION

Hence it can be concluded from above review that thermo physical properties of nanofluids can be predicted with variations in initial steps and it generates relevant information to begin research in nanofluids in developing the next generation of cooling technology. Further, a highly conducting and stable nanofluid with exciting newer

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applications can be used for enhancing the efficiency of safety systems much better in coming future for Nuclear Power Plants.

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