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Nanofluid Heat Transfer Enhancement for Nuclear Reactor Applications

Jacopo Buongiorno*, Lin-wen Hu

Massachusetts Institute of Technology (MIT)
77 Massachusetts Avenue, Cambridge, MA 02139, U.S.A.
*jacopo@mit.edu, +1(617)253-7316

ABSTRACT

Colloidal dispersions of nanoparticles are known as 'nanofluids'. Such engineered fluids offer the potential for enhancing heat transfer, particularly boiling heat transfer, while avoiding the drawbacks (i.e., erosion, settling, clogging) that hindered the use of particle-laden fluids in the past. At MIT we have been studying the heat transfer characteristics of nanofluids for the past five years, with the goal of evaluating their benefits for and applicability to nuclear power systems (i.e., primary coolant, safety systems, severe accident mitigation strategies). This paper will summarize the MIT research in this area with particular emphasis to boiling behavior, including, prominently, the Critical Heat Flux limit and quenching phenomena.

1. INTRODUCTION

Increasing the power density (i.e., power produced per unit volume of the reactor core) of operating and/or future Light Water Reactors (LWRs) is an effective approach to improving their economic attractiveness. Because the capital cost of a typical LWR constitutes ~65% of the total power cost, extracting more energy from an existing reactor or reducing the physical size of future LWRs may reduce the total cost of nuclear power considerably. There are various approaches to uprating the power of a LWR. First, through careful management of the fuel assemblies in the core, it is possible to flatten the power distribution and thus extract more energy from each assembly on average [1]. Second, using advanced fuel designs, including non-traditional geometries such as annular fuel [2] or non-traditional materials such as silicon carbide clad [3], it is possible to operate the core at higher power density while maintaining the safety margins. An alternative approach consists in seeding the water coolant with nanoparticles, to realize a fluid with superior heat removal capabilities, which would in turn allow for operation of the reactor at a higher power rate. The combination of nanoparticles and water is called a 'nanofluid'. This keynote presentation will survey the work done at MIT on nanofluid coolants for nuclear power applications. A synopsis of the presentation is reported in this paper. More detailed information on this topic is available in our journal papers [4,5].

2. THERMAL LIMITS FOR LWRs

There are two physical phenomena that limit the thermal power of a LWR: the so-called Critical Heat Flux (CHF) and 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 (shown in Fig. 1) can 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 (shown in Fig. 1) 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 hypothethical 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.

It is clear from the brief discussion above that an enhanced the CHF and a rapid quenching process are desirable attributes for the nuclear reactor coolant. Dispersing nanoparticles in water is an effective way to enhance CHF and accelerate quenching, as explained next.
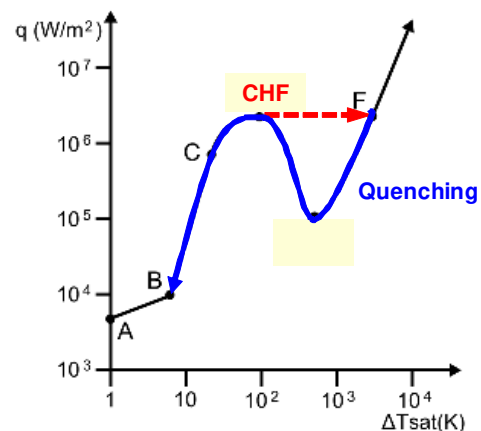

Fig 1. Representative boiling curve for water, highlighting the CHF transition (red arrow) and the quenching process (blue curve).

3. NANOFLUIDS

Numerous studies have reported a very sizable enhancement of the CHF when using nanofluids in pool boiling experiments. The materials, experimental conditions and results of these

studies are summarized in Table 1. Note the relatively low concentration of nanoparticles (<1% vol) sufficient, in most cases, to produce such large CHF enhancements.

The CHF enhancement has been shown to occur also in flow (vs pool) boiling (Figs 2 and 3), which is the situation of interest for nuclear applications. Interestingly, the flow boiling heat transfer coefficient was found to be unaltered by the nanoparticles, within the typical experimental uncertainty for heat transfer tests (Fig 4). Therefore, this (very limited at the present time) data suggest that one could get a situation in which the nanofluid increases the CHF, but not the boiling heat transfer coefficient. Since what limits the reactor power is the CHF, the overall benefit of using a nanofluid coolant in the reactor should be preserved.

Table 1. Main pool boiling CHF tests with nanofluids.

Ref	Nanofluid(s)	Heater type	Max CHF enhancement
[6]	Al_2O_3 in water, 0.001-0.025 g/L	Cu plate	200%
[7]	SiO_2 (15-50 nm) in water, 0.5 v%	NiCr wire	60%
[8]	Al_2O_3 (38 nm) in water, 0.037 g/L	Ti layer on glass substrate	67%
[9]	TiO_2 (27-85 nm) in water, 0.01-3 v%	Cu plate	50%
[10]	Al_2O_3 (70-260 nm) and ZnO in water Al_2O_3 in ethylene glycol	Cu plate	200%
[11]	Al_2O_3 (10-100 nm) in water, 0.5-4 v%	Stainless steel plate	50%
[12]	TiO_2 (85 nm) in water, 10^{-5}-10^{-1} v%	NiCr wire	200%
[13]	SiO_2, CeO_2, Al_2O_3 (10-20 nm) in water, 0.5 v%	NiCr wire	170%
[14]	Au (4 nm) in water	Cu plate	175%
[15]	SiO_2 (20-40 nm), ZrO_2 (110-250 nm), Al_2O_3 (110-210 nm) in water, 0.001-0.1 v%	Stainless steel wire	80%

Fig 3. Flow CHF vs exit quality (X_e) for zinc-oxide-water and diamond-water nanofluids. (From [16])
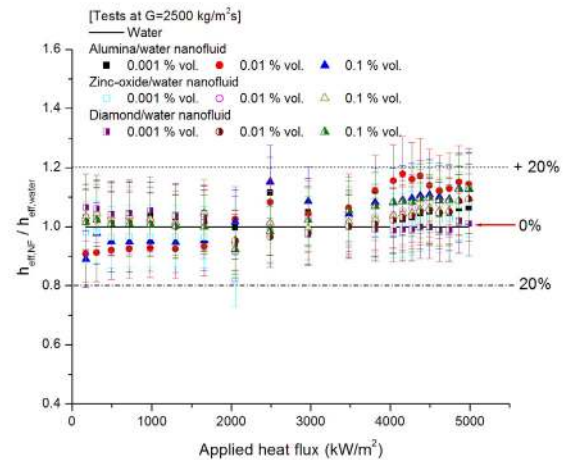
Fig 4. Ratio of nanofluid heat transfer coefficient to pure water heat transfer coefficient in flow boiling. (From [17])

In quenching tests with metallic spheres first heated to ~1000°C, and then rapidly plunged into a pool of fluid at 100°C, it has been shown that the quenching process is greatly accelerated if the spheres are repeatedly quenched in a nanofluid instead of pure water (Fig 5). Using the inverse heat transfer method, the boiling curves associated with the quenching process could be calculated; the results are shown in Fig 6. Note that the presence of the nanoparticles results in an increase of the nanofluid CHF, transition boiling heat transfer rate and minimum heat flux point, all of which are beneficial features.
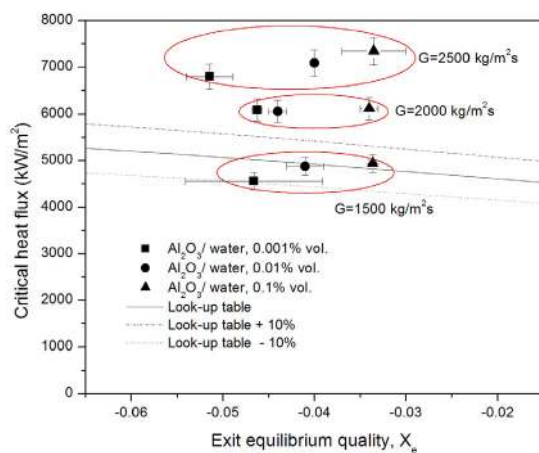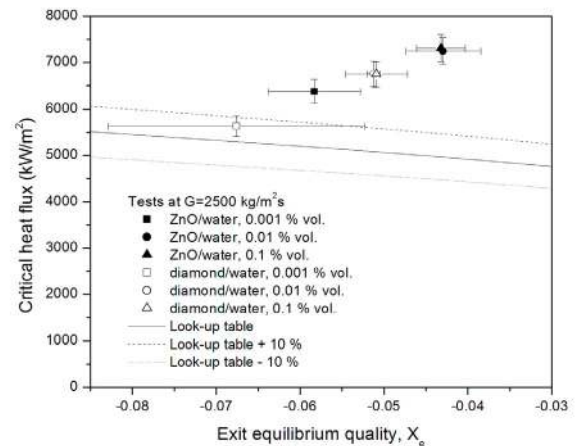

Fig 2. Flow CHF vs mass flux (G) and exit quality (X_e) for alumina-water nanofluids. The look-up table curves are representative of the CHF values for pure water. (From [16])
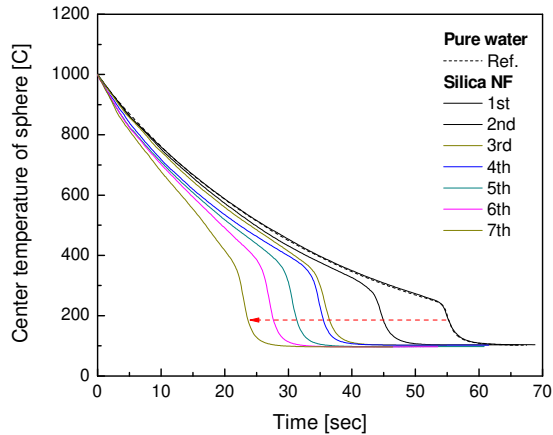
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Fig 5. Temperature history of a 10-mm diameter steel sphere (as measured by a thermocouple at the center of the sphere) quenched in nanofluid. Note the curve shift to the left as the test is repeated 7 times, indicating an acceleration of the quenching process with each repetition. (From [18])
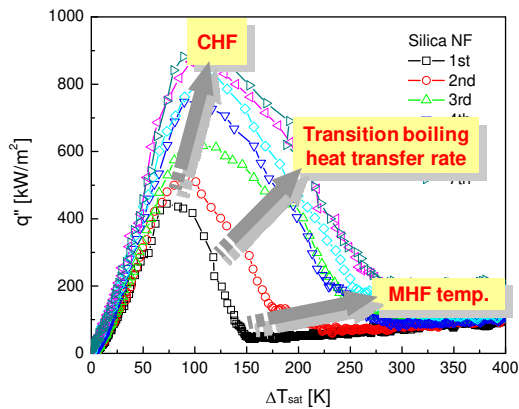

Fig 6. Evolution of the boiling curve when repeated quenching tests are performed in the nanofluid. (From [18])

Similarly beneficial effects were observed when hot rodlets were heated up to 1000°C and then quenched in nanofluids. The cylindrical (vs spherical) geometry is more relevant to the nuclear reactor applications, as the nuclear fuel is used in the core in the form of long rod bundles. With the cylindrical geometry, quenching occurs via the development of a 'quench front' which moves up the rod at a speed of ~1 cm/s (Fig 7). However, when the rod was quenched repeatedly in a nanofluid, the quenching process was so fast that a distinct 'quench front' could not even be observed (Fig 8). Such ultra-fast return to nucleate boiling would lower the maximum temperature attained by the nuclear fuel in a loss of coolant accident, if the emergency coolant were a nanofluid instead of water. More information on quenching heat transfer in nanofluids can be found in other papers [18,19].
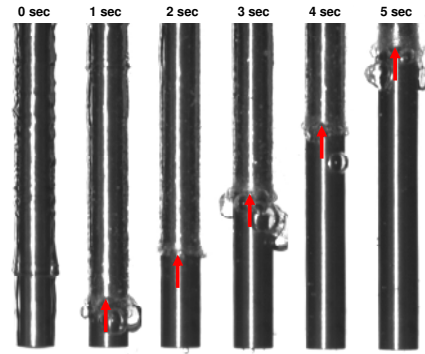

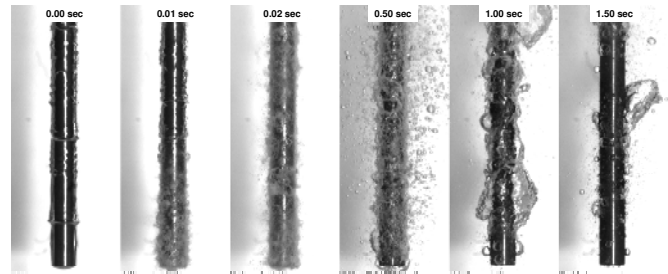Fig 7. Quench front slowly moving up a clean rod quenched in pure water. (From [19])

Fig 8. Ultra-rapid quenching of a 10-mm diameter cylindrical steel rod in nanofluid. Note the time scale difference with respect to the pure water tests in Fig 7. (From [19])

Both the CHF and quenching results point to enhancement mechanisms associated with a surface effect. In fact, upon boiling of a nanofluid, some nanoparticles do deposit on the boiling surface, as shown in Fig 9. This nanoparticle deposition layer has been shown to increase surface roughness (Fig 9) and wettability (Fig 10), both of which could be linked to CHF enhancement [15] and quenching acceleration [19].
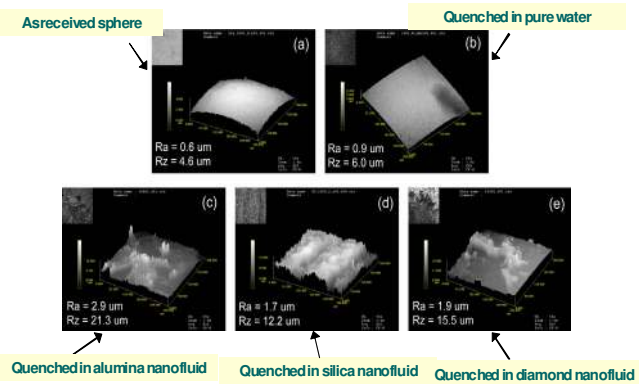

Fig 9. Confocal microscopy images of (a) as-received clean sphere, (b) sphere quenched in pure water, (c)-(e) spheres quenched in various nanofluids. The peak structures on the surface represent the nanoparticle deposits. (From [19])
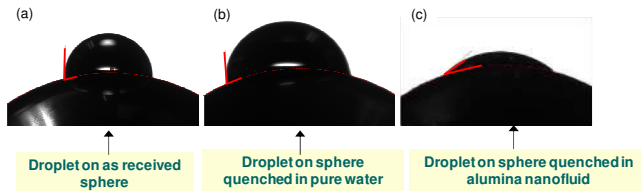
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Fig 10. Static contact angle of a wtaer droplet on (a) as-received clean steel sphere, (b) steel sphere quenched in pure water and (c) steel sphere quenched in nanofluid. Low contact angles indicate high surface wettability. (From [19])

Some researchers have also reported large enhancement of the single-phase convective heat transfer coefficient with nanofluids, e.g., [20-22]. Interestingly, in convective heat transfer experiments conducted at MIT [23,24] with alumina-water and zirconia-water, it was shown that if the *measured* temperature- and loading-dependent thermal conductivity and viscosity of the nanofluids are used in calculating the Reynolds, Prandtl and Nusselt numbers, the existing correlations accurately reproduce the convective heat transfer and viscous pressure loss behavior in tubes within measurement uncertainty. This is shown in Fig 11 for turbulent heat transfer and in Fig 12 for the viscous pressure drop. Therefore, no anomalous heat transfer enhancement was observed in the MIT experiments. This topic is still somewhat controversial; however, at the very low nanoparticle concentrations needed for the CHF and quenching gains, the single-phase convective heat transfer coefficient and viscous pressure drop of the nanofluids are expected to be indistinguishable from those of pure water.
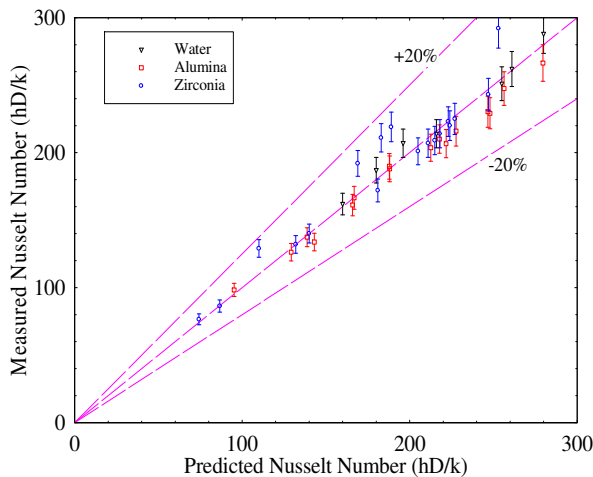

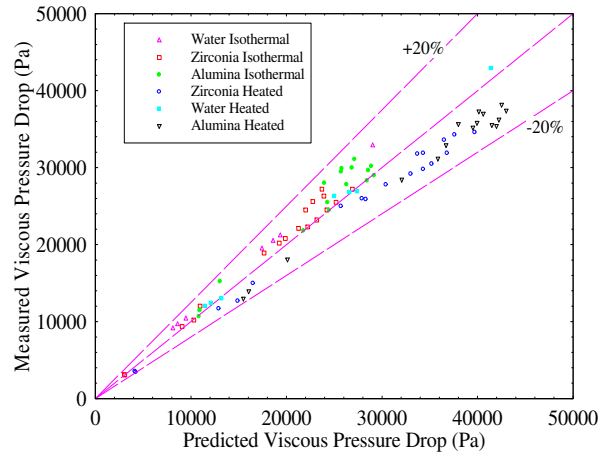Fig 11. Nanofluid Nusselt number in turbulent flow. (From [23])

Fig 12. Nanofluid pressure drop in turbulent flow. (From [23])

In addition to enhanced thermal performance, the requirements for nanofluid coolants to be used in nuclear systems include:

i) Minimal impact of the nanoparticles on the *neutronic behavior* of the core, to maintain the safe and cost-effective operation of current LWRs. Fortunately, at the low nanoparticle concentrations required to obtain the CHF and quenching heat transfer gains, virtually all nanoparticle materials (save strong neutron absorbers such as boron or cadmium) have negligible impact on neutron transport in the core [4].

ii) Minimal *activation* of the nanoparticles upon neutron bombardment, to avoid excessive coolant radioactivity during steady-state and refueling operation. This requirement limits the nanoparticle material selection to materials of low neutron activation (e.g., carbon) or whose products of activation decay rapidly (e.g., silica, alumina) [4].

iii) Compatibility of the nanoparticles with the reactor's *chemical and radiation environment*. Nanoparticles are colloidally stabilized either by controlling the fluid pH or using surfactant stabilizers, or a combination of the two approaches. However, the pH of the water coolant in a LWR is not an independent variable; in fact, it is carefully controlled within a tight range to minimize the corrosion rates throughout the plant. Changing the pH to accommodate the nanoparticles would not be acceptable, so the challenge becomes selecting a nanoparticle material that is chemically and colloidally stable in the established chemical environment of LWRs. Furthermore, the use of surfactants is probably unfeasible, as their complex molecules are easily broken by the intense radiation field in the core.

iv) No *erosion* of the reactor piping and vessel by the nanoparticles. As they have low mass and inertia, the nanoparticles tend to follow the fluid streamlines, and not impact the surrounding surfaces, so their erosion potential should be low. This has been anecdotally confirmed by the erosion-free operation of the flow loops in our lab; however, a more systematic study of nanoparticle-induced erosion is needed, if nanofluids are to be used in the circulating loops of a LWR.

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v) Low *cost* of the nanoparticles. Save the use of expensive noble metals, nanoparticles are produced in large quantities at relatively low cost. For example, stable 6% vol. concentrated alumina-water nanofluid, which yields ~600 times more nanofluid volume if it is diluted to 0.01% vol., runs at about $50 per gallon. Therefore, the cost of the nanofluid per se would be easily offset by the benefits of having a higher power density in the reactor core, even if only a few percent power uprate is achieved.

At the present time, item (iii) above is probably the chief challenge facing the use of nanofluids in nuclear systems. This challenge can be somewhat mitigated (but not entirely eliminated) if the use of nanofluids is limited to the emergency core cooling system, thus keeping the nanoparticles out of the circulating coolant during normal operation.

4. CONCLUSIONS

The thermal characteristics of nanofluids have been surveyed with particular attention to their boiling heat transfer behavior. It was shown that the nanoparticles can enhance the Critical Heat Flux limit and accelerate quenching heat transfer. These findings can be exploited in water-cooled nuclear reactors to realize sizable power uprates in the core, thus attaining significant economic gains or improved safety margins.

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