Rod-type quench performance of nanofluids towards developments of Advanced PWR nanofluids-engineered safety features

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Abstract. Nanofluids, colloidal dispersions of nanoparticles in a base fluid such as water can afford very significant Critical Heat Flux (CHF) enhancement. Such engineered fluids potentially could be employed as advanced coolants in nuclear-engineered safety systems such as Emergency Core Cooling System (ECCS) and External Reactor Vessel Cooling System (ERVCS) with significant safety and economic advantages. When the potential application of nanofluids comes to ECCS, the situation of interest is quench phenomena of fuel rods during reflooding of emergency coolants. Therefore, we experimentally investigate the effect of nanoparticles on the cooling performance of the Inconel 600 cylindrical rod during quenching. This paper provides the first insight based on considerations of promising mechanisms to the rod-type quench performance and phenomena of nanofluids.
KEYWORDS: Nanofluids; Quenching; Boiling; Critical Heat Flux; ECCS; Safety System

1. INTRODUCTION

Nanofluids as fluids that harbor nano-sized particles or engineered colloids are a new type of heat transfer coolants. Their initial concepts suggested by Choi [1] started with an idea that solids have thermal conductivities that are orders of magnitude larger than those of traditional heat transfer fluids such as water, ethylene glycol and refrigerants. That means particles-fluid mixtures have higher thermal performances than conventional fluids due to suspended nanoparticles. More attention in nuclear engineering has been mainly focused on critical heat flux (CHF). Many researchers have reported meaningful enhancement of pool boiling CHF due to surface modification/depositions by nanoparticles during nucleate boiling resulting in improved wettability [2-7] and thermal dissipation [8]. Therefore, such engineered fluids potentially could be employed as advanced coolants in nuclear-engineered safety systems such as Emergency Core Cooling System (ECCS) and External Reactor Vessel Cooling System (ERVCS) with significant safety and economic advantages. Especially, when the potential application of nanofluids comes to ECCS, the situation of interest is quench phenomena of fuel rods during reflooding of emergency coolants. Therefore, the main objective of the present study is to investigate the effect of nanoparticles on the quench performance and phenomena of a rod-shape cylinder. This paper shows the effect of nanoparticles in low concentration as a first-ever report of the rod-type quenching efficiency of nanofluid for nuclear power plants.

2. NANOFLUID PREPARATION AND PROPERTIES

We have selected nanofluids with SiC nanoparticles for their high thermal conductivity and growing interests for nuclear applications. The nanoparticles are dispersed into de-ionized water to prepare a solution of 0.001 % by volume. In terms of colloidal stability, isoelectric point (IEP) is an important factor to decide whether colloidal particles can be stably dispersed in a base fluid or not. SiC nanoparticles have the known value of pH 2.5. The current nanofluid has a pH value far from the IEP which means the colloidal dispersion is stable without significant precipitation.
Nanoparticles in dispersion have a type of spherical shape and 142 nm diameter in average with a normal distribution as shown in Figs. 1 and 2 while it is should be noted that the primary particle size

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of the SiC nanoparticles is below 100 nm as shown in the TEM image. Table 1 shows the physical properties through thermal-fluid characterization by using pH/conductivity meter, a transient heated needle method for thermal conductivity, viscometer, and a ring-type surface tension analyzer [9].

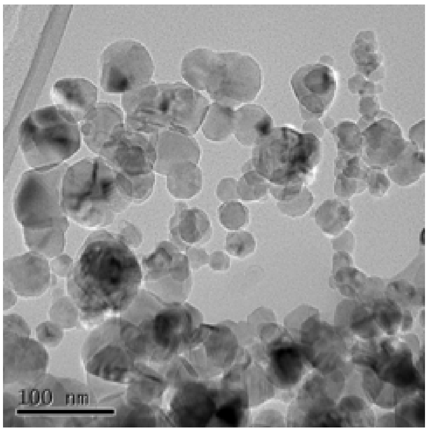


Fig. 1. Morphology of SiC Nanoparticles (TEM).

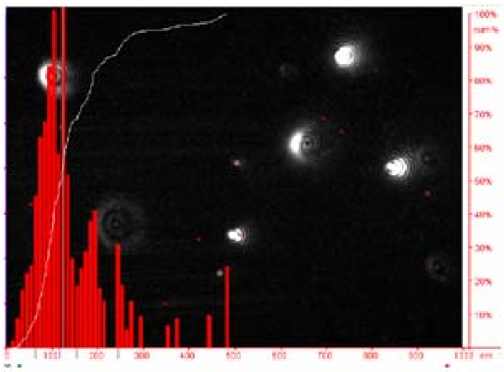


Fig. 2. Size Distribution of SiC Nanoparticles.

2. QUENCH EXPERIMENTS

2.1. Nanofluid Quench Facility

Quench phenomena have been investigated by using the nanofluid quench facility, which consists of a data-acquisition system, a furnace, a cylinder tank for fluids and thermocouple-connecting rod-coupling cylindrical specimens. Cylindrical specimens (see Fig. 3) were machined from Inconel 600; they were 12.5 mm in diameter and 60 mm long. The surface of all the specimens was polished to ensure or help repeatability of the quenching results. The specimens were equipped with type K sheathed thermocouple of 1.5 mm diameter buried at mid-length at a depth of 30 mm.

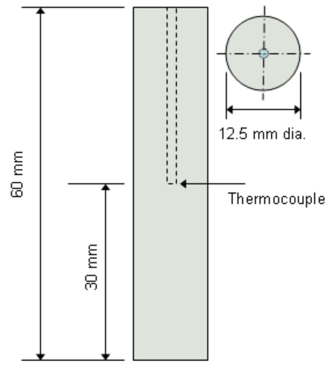


Fig. 3. Drawings of the Quench Specimen.

2.2. Procedure

The test procedure is first to preheat the quench specimen in the furnace until a predefined temperature is reached in the range of 850 ^{o}C. Each specimen was quickly removed from the furnace to be quenched in 30 ^{o}C water. The temperature history was recorded on a personal computer at a frequency of 10 Hz. In addition, quenching phenomena are carefully investigated with initiation of quenching by using high-speed camera (Photron, FASTCAM-APX) with 1024 x 1024 resolution image sensor and 3000 fps frame rate at full resolution. It is noted that the uncertainty of temperatures is within 1 ^{o}C based on initial calibrations.

3. RESULTS AND DISCUSSION

3.1. Cooling Curve

Fig. 4 illustrates centerline temperature histories recorded during quenching for water and SiC nanofluids, as well as atmospheric environment. As it can be seen in the Figs. 5 and 6, SiC nanofluid had a better cooling performance compare to water. Still-air cooling rate is also compared. For a better understanding of the data, the measured time durations required to reduce the centerline temperature up to a fixed temperature and values of cooling rate at max. and 300 ^{o}C are reported in Table 2.
In general, heat transfer during quenching can be described by three governing phases: film boiling, nucleate boiling, and convective boiling. The modes of heat transfer correspond to three distinctive slopes of each curve except air in Fig. 4. For reference, the current specimen is not applicable to getting heat transfer coefficient because the dimension of cylindrical specimen has too large Biot number (>0.1) to apply lumped capacitance method of Equation (1).

$$-hA_s(T - T_\infty) = \rho VC\frac{dT}{dt} \quad (1)$$

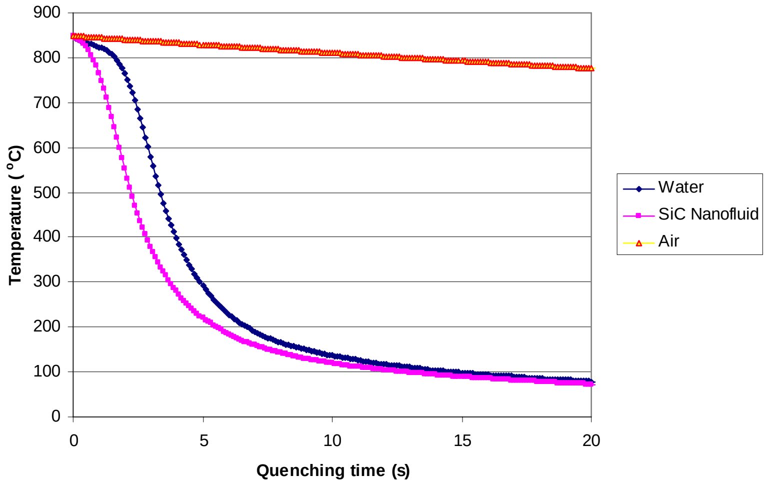


Fig. 4. Temperature History for the Quench Tests.

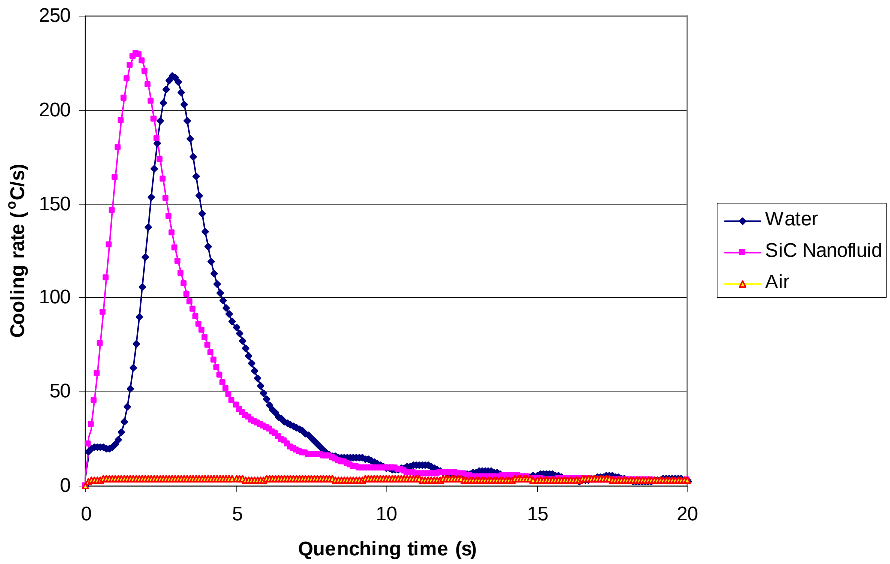


Fig. 5. Comparison of Cooling Rates vs. Time.

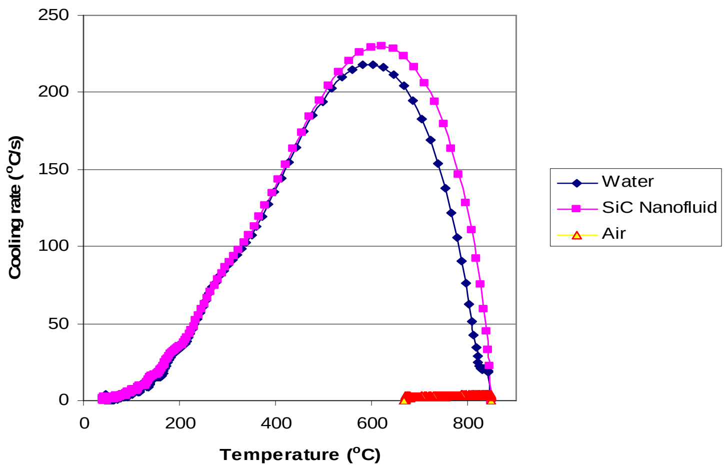


Fig. 6. Comparison of Cooling Rates vs. Temperature.

3.2. Quench phenomena and quench front (QF)

The present section is introduced to physically investigate the effect of nanoparticles dispersed into water on a rod type quench phenomena represented by rewetting of liquid phase on reflood process during postulated loss-of-coolant accidents (LOCA). Rewetting is well known to be essential to establish normal and safe temperature levels of nuclear fuel rods. Rewetting is the re-contact of liquid with a hot surface of overheated fuel rods. A quench front (QF) is defined as the edge of the contact area, which is advancing by progressive cooling of the surface. A quench velocity (or rewetting velocity) means such advancing velocity of the border and the apparent temperature, at which a surface of nuclear fuel rods starts to be cooled quickly and reduced to nearly saturated temperature in a short time, is called a quench temperature [10]. Therefore, QF and rewetting phenomena are essential to physically understand the effects of nanoparticles/naofluids resulting in change of the cooling rate.

3.2.1. Propagation of quench front

Fig. 7 (a) illustrates the propagation of QF in the range of its velocities 7.29-9.1 mm/sec observed in water quench test by using a high-resolution motion camera while Fig. 7 (b) shows that with similar velocity range of ~9 mm/sec for SiC nanofluid. It is noted that SiC nanofluid is too opaque to observe by naked eyes clearly, which required an image processing with brightness/contrast enhancement for Fig. 7 (b). The QF observations also shows well that the progression of the QF is axial-conduction-controlled typically and heat transfer mode of transition boiling most likely controls the propagation of the QF, in the narrow QF region as reported by Yadigaroglu et al. [11]. An approximate expression on the quench velocity from a two-dimensional Fourier equation of heat conduction has analytically derived as Eqs. (2) and (3) by Duffey and Pothouse [12]. It is based on the order of magnitude of the heat transfer coefficient for wetting (~10^4 W/m^2•ºC) compared to the one (~10^2 W/m^2•ºC) ahead of wetting [10].

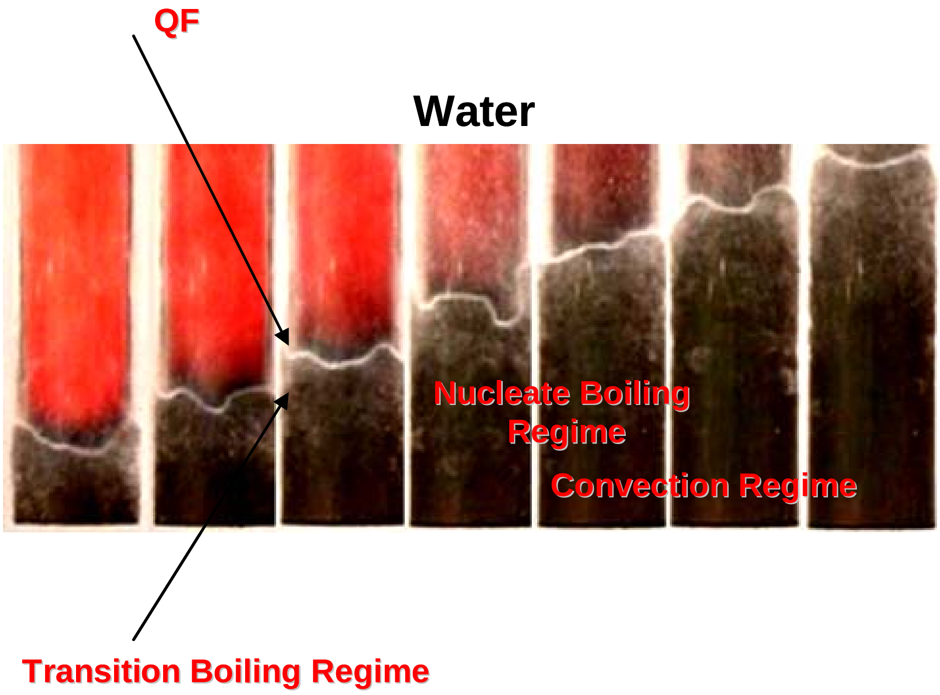
For Bi«1,

$$u_{QF}^{-1} = \rho C \left(\frac{\varepsilon}{h_{QF} k} \right)^{1/2} \frac{(T_w - T_s)^{1/2} (T_w - T_L)^{1/2}}{(T_L - T_s)} \quad (2)$$

For *Bi*»1,

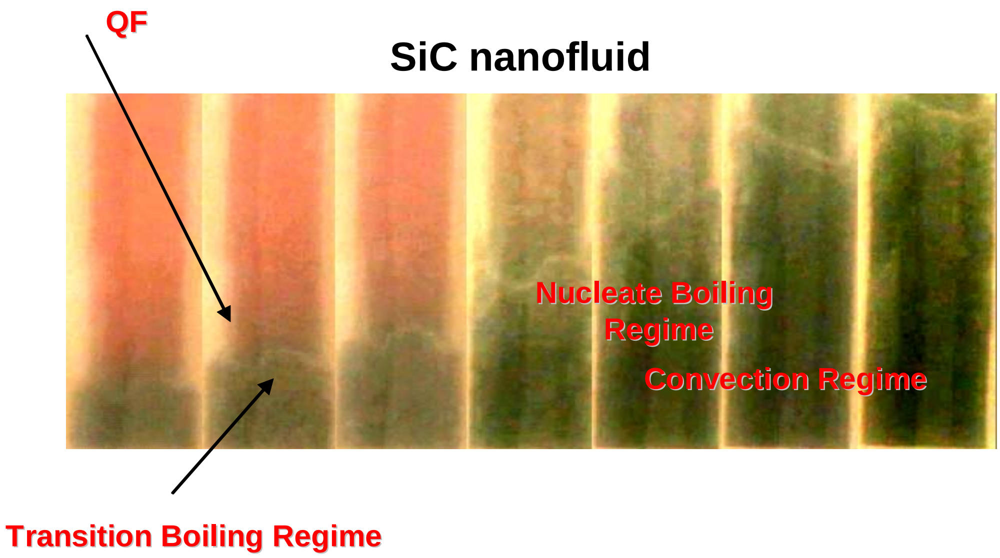
$$u_{QF}^{-1} = \frac{\pi \rho C k}{2 h_{QF}} \cdot \frac{(T_w - T_s)}{(T_L - T_s)} \quad (3)$$

From the Eqs, simply if nanofluid has larger heat transfer coefficient than water in QF or higher Leidenfrost temperature, we can expect that quench velocity would be increased. However, it is too early to judge it because the experimental correlations are not based on physical mechanisms. On the other hands, it has been reported that deposition layer of nanoparticles on a surface induced by nanofluid-vaporization showed efficient thermal dissipation of hot spots in near- or CHF condition as shown in Fig. 8 [8]. It could be considered to drive more efficient axial conduction-induced thermal dissipation of heat which is described by the ‘thermal effusivity’: $(\rho Ck)^{1/2}$. Thermal properties of the material of interest are reported in Table 3. However, the images in Fig. 7. do not show clear difference between pure water and SiC nanofluid. It might be due to low concentration of nanofluid which is used in this study.



#1 #2 #3 #4 #5 #6 #7

(a) QF with the max velocity of ~9 mm/sec. in water



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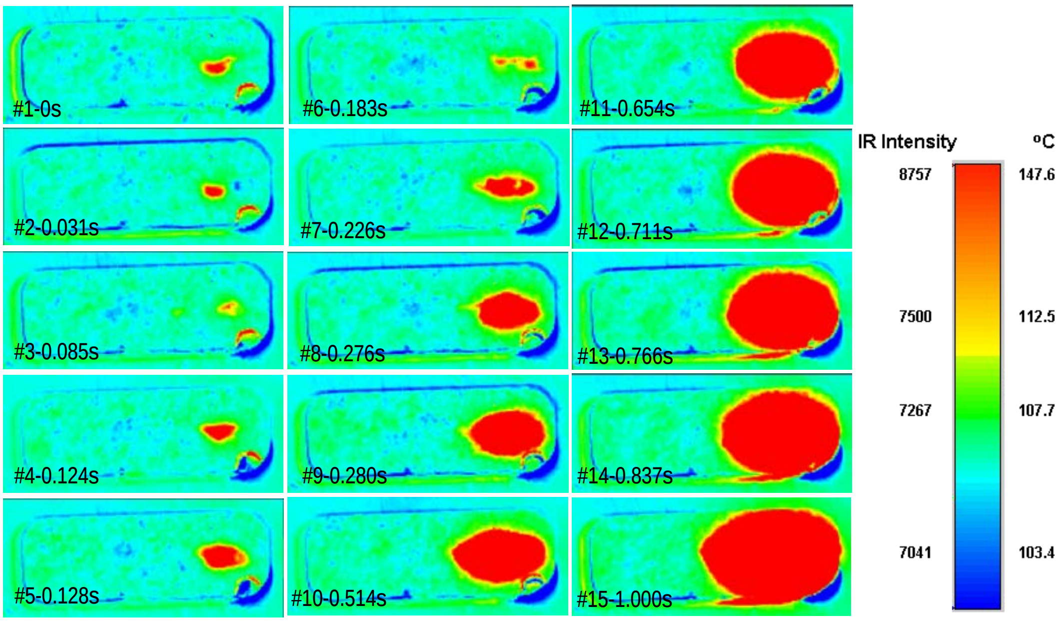
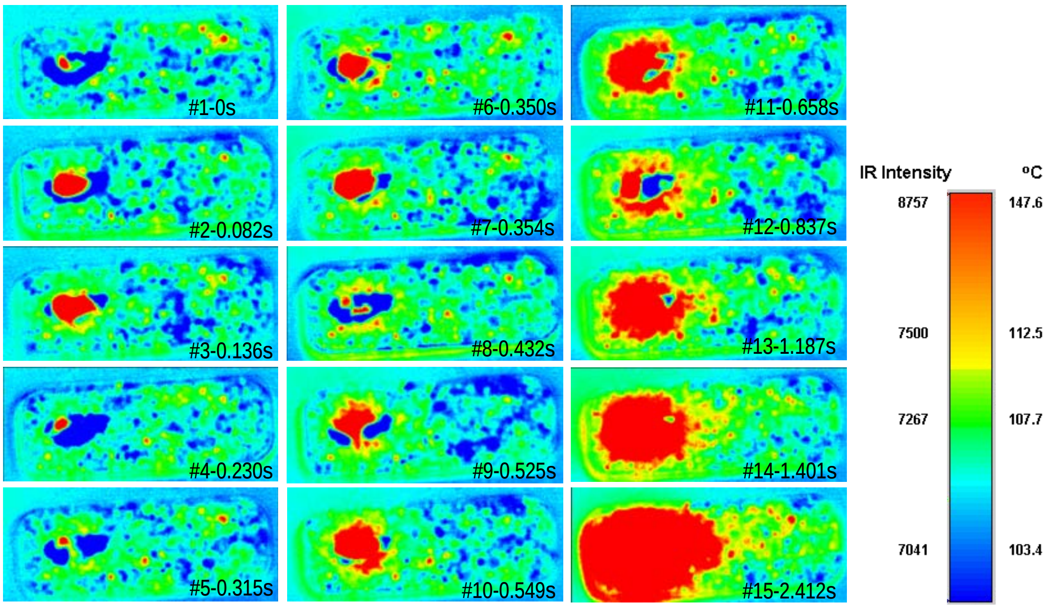
(b) QF with the max velocity of ~9 mm/sec. in water

Fig. 7. Propagation of Quench Front (QF).



(a) pure ethanol (~480kW/m^2)



(b) ethanol-based alumina nanofluid (~530 kW/m^2)

Fig. 8. IR images of CHF [8].

3.2.2. Layer of vapor blanket/film

The thickness of vapor film surrounding hot parts of the rod and separated from bulk liquid is estimated as ~ 0.345 mm for both liquids. As other considerable mechanisms, improved radiation heat transfer could reduce thickness of vapor film and turbulence-enhancement by nanoparticles for the interfacial area between vapor film and bulk liquid could make early and irregular rupture of vapor film surrounding the hot rod. It would cause locally nonuniform cooling in nanofluids quenching.
Efforts to substantially observe such nanoparticles effects on QF are currently being made as shown in Fig. 9. The images acquired from the high-speed camera can show more detailed physical mechanisms

for the effect of nanoparticles on quenching phenomena. However, the opacity of nanofluid usually hinders clear visualization of the quenching phenomena.

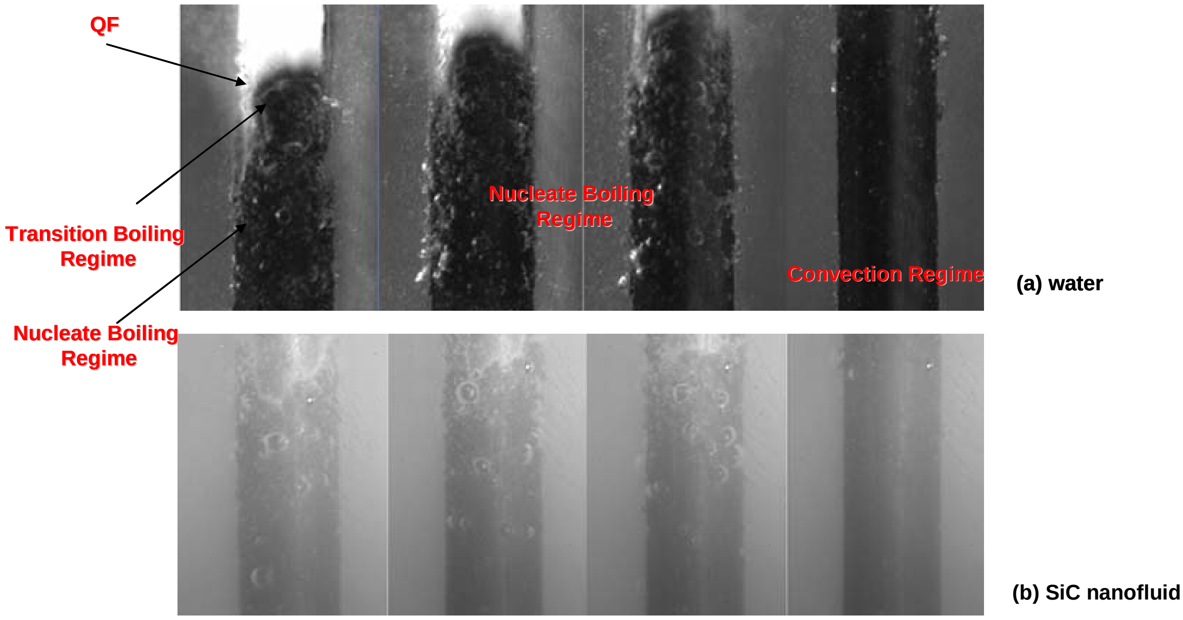


Fig. 9. Comparison of Quench Phenomena.

4. CONCLUSIONS

The present work experimentally investigated the effect of nanoparticles on the cooling performance of the Inconel 600 cylindrical rod during quenching. This paper provides the first insight to a rod-type quenching performance and phenomena of nanofluids. We observed the maximum cooling rate of SiC nanofluid (230 ^{o}C/s) is faster than pure water (218 ^{o}C/s). Mechanistic changes expected from using nanofluid as a new coolant of an ECCS can be suggested as follows;

- improved heat transfer coefficient of nanofluids in QF
- improved thermal dissipation accelerating QF
- locally nonuniform cooling in nanofluids
- rupture of vapor blanket/film due to turbulence enhancement
- improved radiation heat transfer of nanofluids
- improved surface wettability by nanoparticles

It is noted that the more detailed investigation should be done because of general trend of a nanotechnology lacking consistency. Therefore, a more systematic study of the effect of fluid temperature, nanomaterials and concentration on the quenching efficiency will be further carried out.

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