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An Experimental Study of the Steel Cylinder Quenching in Water-based Nanofluids

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ABSTRACT

In this study, some parameters such as quenching and boiling curves of a stainless steel cylindrical rod 80 mm long and having a diameter of 15 mm were experimentally obtained in saturate pure water and two nanofluids (SiO_2 and TiO_2) with 0.01 wt%. The cylinder was vertically lowered into the pool of saturated water and its temporal center temperature was measured by a thermocouple. The boiling curves were then obtained by solving a transient one-dimensional inverse heat conduction model and measuring the temperature at the center of the cylinder. The images of the surface morphology and uniformity of the deposited SiO_2 and TiO_2 nano particles were captured by the scanning electron microscope (SEM). The cooling time during quenching of the cylinder was decreased about 50% by nanoparticles deposition. However, the SiO_2 and TiO_2 nano particle deposition have similar critical heat flux increment (up to 120%). Film boiling heat transfer rate increased by repetitive quenching in SiO_2 nanofluid.

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NOMENCLATURE

A	Surface area of cylinder , m^2	σ	Surface tension
C_P	Specific heat, J/kg K	τ	Wall shear stress, Pascal
CHF	Critical heat flux, W/m^2	**Subscripts**	
MHF	Minimum heat flux, W/m^2	c	center of cylinder
T	Temperature, ˚C	FB	Film boiling
Greek Symbols		sat	refer to saturate condition
ρ	Density (kg/m^3)	v or g	refer to vapor properties

1. INTRODUCTION

A simple quenching experiment can be used to demonstrate and study the heat transfer phenomena in different boiling regimes corresponding to different regions of the boiling curve. This process starts with film boiling and then transition boiling, nucleate boiling and natural convection, respectively. Quenching involves immersion of a higher temperature object than the ambient temperature in a liquid. Various parameters such as initial surface temperature, surface properties, surface orientation, and agitation of the fluid affect the quenching heat transfer [1].

In all of the water cooled nuclear reactors such as pressurized water reactors (PWRs), pressurized heavy water reactor (PHWR) and boiling water reactors (BWRs) quenching plays an important role. In a light water reactor (LWR), when a loss-of-coolant accidently occurred, the clad surface temperature due to low heat transfer of the surrounding steam, quickly increases. At this time, water is injected from the emergency cooling systems to keep the integrity of the core. Because of high temperature of the clad surface, water does not initially wet the clad surface and a thin vapor film forms between the clad surface and the cooling water. Rewetting of a hot surface occurs when the coolant reestablishes contact with the dry clad surface, in other words, heat transfer regime changes from film boiling to transition or nucleate boiling.

However, it should be noted that the rate of heat transfer is limited by the Leidenfrost effect during quenching or boiling processes. The minimum film

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boiling temperature, T_{MFB}, is sometimes called the Leidenfrost temperature, T_{Lei}. Many methods have been suggested to decrease the Leidenfrost effect and boost boiling heat transfer. Examples include shaking the heating surface, increasing the heating surface area, and using an electric field to increase bubbles parting speed [2]. Thanks to recent developments in nanotechnology, a new group of fluids has been produced, called nanofluids, by scattering particles in the nanometer size range in a base fluid. These nanofluids are known to have the capacity to boost heat transfer in fluids [3].

Recently, scientists have found that heat transfer coefficient (HTC) and CHF was not directly enhanced by nanofluids [2-4]. They investigated that this improvement is due to changes in the macroscopic surface properties such as roughness and wettability [5-10]. In addition, Kim et al. [10] showed that the surface parameters (roughness and wettability) promoted film boiling heat transfer and film boiling temperature, but they showed that surfaces coated with diamond nano particles did not significantly change the HTC and CHF. This shows that there are still non-negligible effects which are not yet known to researchers.

The objective of this study is quenching of a steel cylinder in TiO_2 and SiO_2 nanofluids and to investigate the effects of nanoparticles deposition on the surface on the boiling heat transfer and boiling margins.

2. EXPERIMENTAL PROCEDURE

2. 1. Apparatus

Schematic diagram of quench test setup is shown in Figure 1. The setup that is used in this experiment includes a stainless steel cylinder, a K-Type thermocouple, a high temperature radiant furnace, a heater, a high speed camera, an agitator, a visible fluid pool (a beaker), one RTD thermometer, a data acquisition system, and a computer.

A data acquisition system with a frequency of 10 Hz was used to record the temporal temperatures at the center of the heated cylinder. The collected data was then transferred to a computer for further analysis.

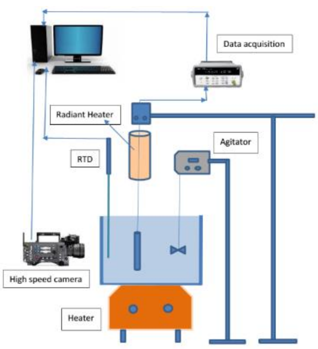


Figure 1. Schematic diagram of the experimental setup (Not to scale)

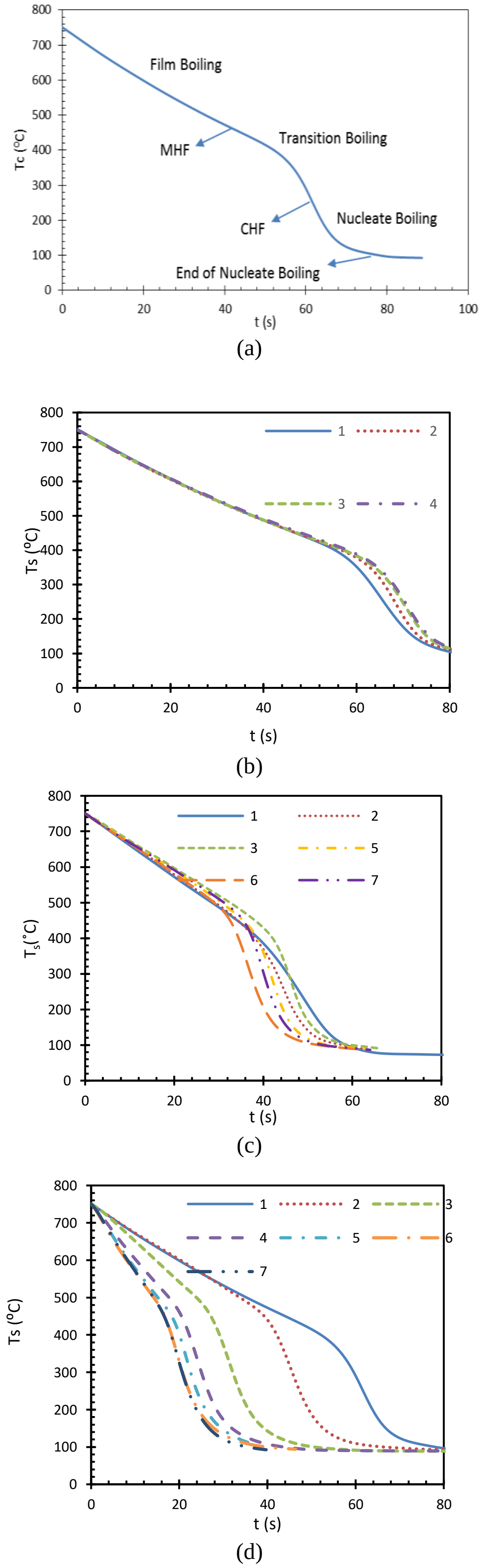


Figure 2. (a) Quenching curve partitioning and quenching curves for repetitive nano coating of cylinder in (b) pure water, (c) TiO_2, and (d) SiO at saturate conditions

The cylindrical pool with 250 mm in diameter and 400mm in height was placed on a heater. The pool measuring system and the size of the SS samples were such that the effects of the rims on the boiling could be ignored.

2. 2. Test Sample A stainless steel cylinder 80 mm long and having a diameter 15 mm was used in this study. The cylinder was drilled at one end to mount a 1 mm O.D. thermocouple of K-type (considering the reinforcement tube) with the measurement uncertainty of ±1 ^{0}C at the center of the cylinder. A good thermal contact was obtained by this technique.

2. 3. Nanofluids Preparation Two nanoparticle materials have been selected for this study, i.e., silica (SiO_2), and titanium oxide (TiO_2). The best method for dispersing nanoparticles in a base fluid is using the method that the amounts of the nanoparticles, was first determined based on the required nanoparticle fraction (0.01 wt%). The fluid containing nanoparticles was stirred well before being placed in the ultrasonic processor which was run at 2A and a frequency of 50 Hz for 40 min. Low concentration of nano particles were used to maintain nanofluid transparent. Unlike TiO_2, SiO_2 is transparent and all boiling phenomena could be seen during the experiments.

2. 4. Experimental Procedure The test samples were thoroughly washed with pure water and acetone prior to the tests in order to avoid surface contaminations. Initially, the high temperature furnace was turned on and set at 1000 ˚C. The hot plate heater was turned on to bring the fluid to saturation temperature and the pool temperature was then recorded by the RTD thermometer.

The test sample was held in the furnace and the temperature in the center of the sample was measured by the thermocouple attached to the data acquisition system. After the cylinder temperature reached slightly above 900 ˚C, the sample was taken out of the furnace and was dropped vertically into the pool. Time was allowed for the sample temperature to reach 750 ˚C before temperature recording was started. Then the boiling and cooling curves were obtained using appropriate theoretical relations.

A transient one-dimensional inverse heat conduction model is solved by an explicit finite difference method.

During the insertion of the rodlet to the fluid, a constant heat flux due to the high speed of the rod immersion is considered. The governing equation for the one-dimensional transient heat conduction within the solution domain can be written as follows:

$$\frac{1}{r}\frac{\partial T}{\partial r}\left(r\frac{\partial T}{\partial r}\right)=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

To calculate the surface temperature and heat flux in a given time, the computed temperatures were compared with the measured temperatures by using the future time steps and the number of thermocouples. S is the sum of the square errors that has to be minimized.

$$S=\sum_{f=m+1}^{m+n_f}\sum_{j=i;i=1}^{n_T}\left(T_i^{*,f}-T_j^f\right)^2 \tag{2}$$

The heat flux, q_m is then updated by the expression given below:

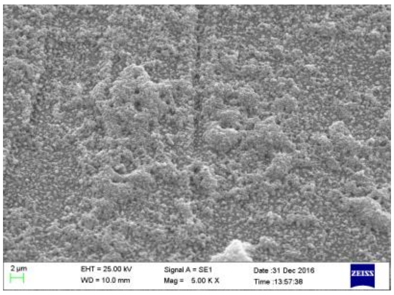
$$q^m=q^{m-1}+\frac{\sum_{f=m+1}^{m+n_f}\sum_{j=i,i=1}^{n_T}\left(T_i^{*,f}T_j^f\right).\phi_i^f}{\sum_{f=m+1}^{m+n_f}\sum_{i=1}^{n_{T^*}}\left(\phi_i^f\right)^2} \tag{3}$$

where ϕ_i^f is the sensitivity of i^{th} thermocouple. The sensitivity coefficient denotes the increase in temperature at the thermocouple location per unit surface heat flux.

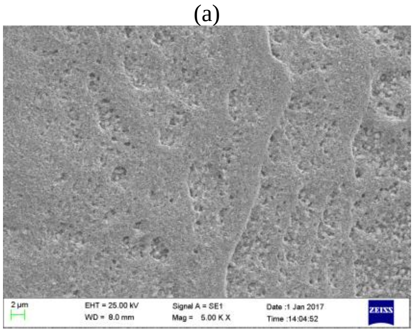
3. RESULTS AND DISCUSSIONS

3. 1. Quenching and Boiling Curve Results Figure 2a illustrates the quenching curve partitioning of a cylinder in a fluid. Prior to the nanofluid tests, test was conducted in pure water. Repetitive quenching of the cylinder that was vertically inserted into pure water, is shown in Figure 2b. It can be seen that quenching curve is rather repeatable. Figures 2c and 2d show the temperature histories for repetitive quenching tests at the cylinder surface, vertically plunged into the TiO_2 and SiO_2 nanofluid, respectively. It is shown that all boiling regions (film, transition and nucleate boiling) are affected and the quenching process is generally faster. As the concentration of nanofluid unchanged or even diminished, due to the particle deposition on the surface, the temperature drop in every repetitive quenching is increased for constant fluid temperature. Therefore, changes that take place in the quench process are almost related to the surface modification. Also, an increase of nanoparticles concentration on the cylinder surface is clearly visible on the SEM images that were captured. The scanning electron microscope (SEM) images are shown in Figures 3a and 3b.

Figure 4a shows the boiling curves of the cylinder in TiO_2 nanofluid. As shown, the MHF point in repetitive tests approximately occur at the same heat flux and cylinder temperature, but the CHF occurs at higher heat fluxes. It was found that using TiO_2 nano particles only enhance the CHF. Figure 4b shows the boiling curves of the cylinder in the SiO_2 nanofluid. It can be seen that the MHF and the CHF both increased with repetitive quenching the cylinder.

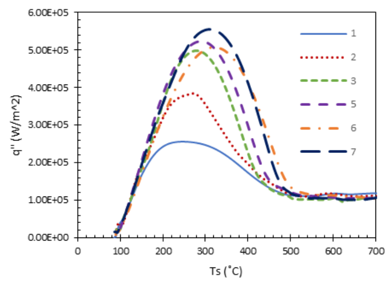


(a)

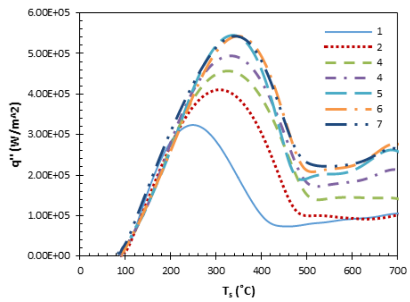


(b)

Figure 3. SEM images of the cylinder surface; (a) surface coated with TiO_2 nanoparticle, and (b) surface coated with SiO_2 nanoparticle



(a)



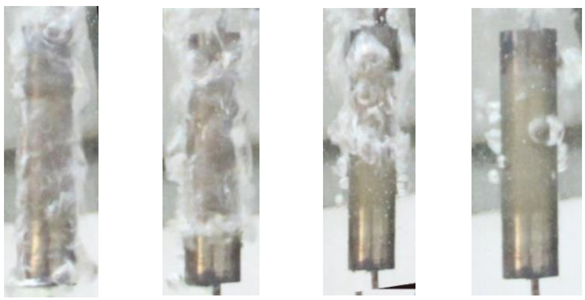
(b)

Figure 4. Boiling curves for repetitive coating, (a) TiO_2 nanofluid, and (b) SiO_2 nanofluid at saturated conditions

As shown in Figures 4a and 4b, the film boiling heat transfer does not change for repetitive quenching in TiO_2 nanofluid, but increases in the SiO_2 nanofluid. Kim et al. [11] investigated that the film boiling heat transfer enhancement is due to an increase in the solid-liquid short-lived contacts. They associated an increase in contact with the surface wettability and increase of surface roughness. The results of this experiment indicate that other factors are also influential. Although, both SiO_2 and TiO_2 nanoparticles deposition increase the surface wettability and roughness, but as shown in Figures 4a and 4b, they exhibit a different behavior in the film boiling region. One of the reasons for increasing the film boiling heat transfer rate of the SiO_2 repetitive quenching is the higher deposition rate of these nanoparticles on the cylinder surface. As shown in Figures 3b and 3c, the SiO_2 nanoparticle deposition rate is larger than TiO_2. For better visibility of the quench phenomenon, images were captured during the transition from film boiling through nucleate boiling. Quenching phenomena of the cylinder at saturated condition in pure water and SiO_2 nanofluid are shown in Figures 5a and 5b, respectively. It can be seen that for a clean surface imersed inside the base fluid, the film boiling region disappears from the bottom of the cylinder and continues to the top. However, when the surface is coated and requenched in the nanofluid, the vapor layer simultaneously collapses on the cylinder.

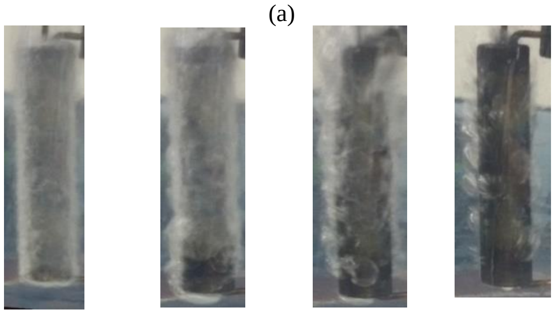
Nishio, Uemura and Sakaguchi [12] [12] investigated that the vapor film can collapse with two modes during quenching: (a) the coherent collapse, Figures 5a and 5(b) the propagative collapse, Figure 5b.

3. 1. 1. CHF and MHF Points In water cooled nuclear reactors, the Leidenfrost (or MHF) point has an important role in the loss of coolant accidents and the



0 s 6s 12 s 18 s

(a)



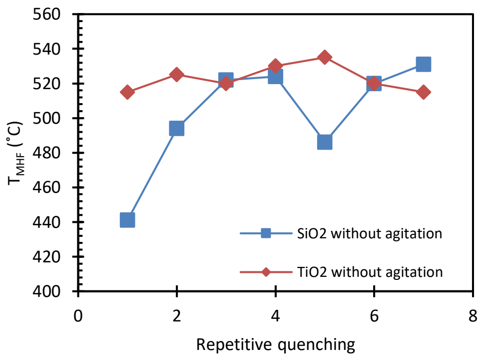
0 s 0.9 s 1.8 s 2.7 s

(b)

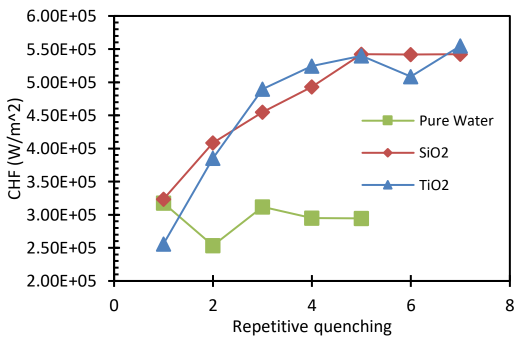
Figure 5. Progress of boiling with time on the cylinder for pure water and SiO_2 nanofluid at saturate condition

mechanism of the emergency cooling systems that spray water on the fuel rods.

Figure 6a shows the MHF point temperature vs repetitive insertion into TiO_2 and SiO_2 nanofluids. Results showed that MHF cannot be predicted by the traditional correlations. Figure 6b shows the CHF versus the repetitive insertion into pure water, TiO_2 and the SiO_2 nanofluids. It can be seen that the CHF of pure water for repetitive insertion was not changed. The CHF for TiO_2 and SiO_2 was significantly increased with repetitive insertion into the pool.



(a)



(b)

Figure 6. Effect of particle deposition on (a) minimum heat flux temperature, (b) critical heat flux versus repetitive quenching

4. CONCLUSIONS

In this study, experiments were conducted to investigate the effect of quenching of a steel cylinder in water-based nanofluids. Using one-dimensional inverse heat conduction method and the measured center temperature, the quenching and boiling curves were obtained for saturate pure water and two nanofluids (SiO_2 and TiO_2) with 0.01 wt%. The main findings of the present investigation can be summarized as follows:

- The slope of the film boiling regime in the cooling curve increases with increasing SiO_2 nano particle deposition, whereas for the TiO_2 it remains almost constant.
- The SEM images showed that cylinder surface with repetitive insertion into the SiO_2 nanofluid becomes smoother than into TiO_2 nanofluid. Cavities are filled with the growing SiO_2 nanoparticle deposition on the surface.
- The slope of the film boiling regime significantly increases with initial quenching tests into SiO_2 nanofluid.
- At initial stage of deposition, increase of CHF of the cylinder surface inserted into SiO_2 is higher than that of the TiO_2. This may be due to higher rate of particle deposition on the cylinder surface.
- MHF temperature is not significantly changed by TiO_2 particle deposition.

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چکیده

در این مطالعه منحنی‌های کوئنچ و جوشش یک میله استیل به طول ۸۰ میلی‌متر و قطر ۱۵ میلی‌متر به صورت تجربی در آب خالص و دو نانوسیال SiO_2 و TiO_2 در حالت اشباع با درصد وزنی ۰.۰۱ بدست آورده شده است. سیلندر به صورت عمودی به درون استخر اشباع وارد شده و دمای مرکز آن بواسطه یک ترموکوپل اندازه‌گیری می‌گردد. منحنی‌های جوشش با استفاده از حل مدل یک بعدی هدایت گرمایی گذرای inverse و اندازه‌گیری دمای مرکز سیلندر بدست آمده است. جهت بررسی مورفورولوژی و یکنواختی ذرات نشسته شده برسطح عکس‌های SEM گرفته شده است. زمان خنک‌سازی در طول کوئنچ سیلندر بواسطه نشست نانو ذرات در حدود ۵۰٪ کاهش یافته است. با این حال، نشست نانو ذرات SiO_2 و TiO_2 افزایش مشابهی (در حدود ۱۲۰٪) در شار حرارت بحرانی دارند. نرخ انتقال حرارت جوشش فیلمی بواسطه کوئنچ‌های مکرر در نانو سیال SiO_2 افزایش یافته است.

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