The Effect of Type of Nanoparticles on the Quenching Process

Dogan Ciloglu, Abdurrahim Bolukbasi, Harun Cifci

***Abstract*—**In this study, the experiments were carried out to determine the best coolant for the quenching process among water-based silica, alumina, titania and copper oxide nanofluids (0.1 vol%). A sphere made up off brass material was used in the experiments. When the spherical test specimen was heated at high temperatures, it was suddenly immersed into the nanofluids. All experiments were carried out at saturated conditions and under atmospheric pressure. After the experiments, the cooling curves were obtained by using the temperature-time data of the specimen. The experimental results showed that the cooling performance of test specimen depended on the type of nanofluids. The silica nanoparticles enhanced the performance of boiling heat transfer and it is the best coolant for the quenching among other nanoparticles.

***Keywords*—**Heat transfer, nanofluid, pool boiling, quenching.

I. Introduction

TODAY'S technology allows manufacturers to make small systems more efficient now than at any time in their production history. These systems are generally faced high heat productions. If this heat is not removed from the system, it means that there is a major problem to continue working without any malfunction. Conventional heat transfer fluids such as water, engine oils or ethylene glycol are used to remove the heat generated. However, these fluids have poor heat transfer properties compared with that of most solids in general. It is a well-known technique to increase the thermal conductivity of the liquid by dispersing solid particles [1]. However, mix of milli- and micrometer-sized solid particles is cause to sedimentation, clogging and erosion of pipes and channels. As is seen, the working fluids in the heat removal have a crucial role for the system performance. With their superior thermal properties, nanofluids offer the engineer opportunities for these systems where a high heat flux, small in size and light in weight are required.

Nanofluids consist of by adding nanoparticles of small size and low centration to water, oil and antifreeze with certain proportions [2]. Low particle size provides large heat transfer surface area, high thermal conductivity, more stable suspension and increased the impact of turbulence and therefore nanofluids use a number of industrial sectors including medicine, automotive industry, the cooling of microelectronic systems and HVAC systems.

Quenching process is the cooling of high temperature solid materials in liquids that uses various industrial applications. For example, steel hardens by slowly or fast cooling in oil or water after heating. On the other hand, quenching plays an important role in reducing accidents that may be caused by the reduction of the refrigerant in nuclear reactors [3]. In the case of insufficient refrigerant in such a reactor, the temperature of the fuel can increase very high temperatures (>1000°C). To reduce of fuel temperature, water spray emergency cooling system is activated. This cooling process is performed by moving the front cooling slowly upwards through the reactor core. Researchers expect that a significant increase in pre-cooling speed and reactor safety with using nanofluids at cooling system of reactor [4]. In general, the presence of a stable vapor film layer on the heater surface has a restrictive effect of heat transfer during the quenching process. So in many applications, it is desirable to accelerate the transition from film boiling to nucleate boiling. Traditional heat transfer fluids (water, ethylene glycol, oil, etc.) are not sufficient to accelerate this transition, but it is expected to accelerate this process of nanofluids [3].

Kim et al. [3] carried out a quenching process of steel and zircaloy spheres in nanofluids. The researchers used in their study at low concentrations (≤0.1 vol %) nanofluids that were prepared alumina, silica and diamond nanoparticles with pure water. They reported that the nanoparticle deposition on the spherical specimen after the repeated experiments caused cooling performance increments.

Park et al. [5] investigated the cooling behaviors at high temperature of stainless steel with using water-based Al_2O_3 nanoparticles coolant. The researchers observed the film boiling heat transfer was lower at nanofluids compared with pure water.

Lotfi and Shafii [6] examined quenching process around a silver sphere at high temperature with nanofluids. As the nanofluid they used Ag and TiO_2 nanoparticles with deionized water. Their results showed that the nanofluids deteriorated the quenching performance and boiling heat transfer coefficient. However they observed that the nanoparticles at pure water prevented the film boiling and nucleate boiling time was increased. Thus sphere was cooled faster in their study. They stated that this effect was due to deposited particles on surface.

Ciloglu and Bolukbasi [7] performed quenching experiments with using brass cylinders at water-based nanofluids. They reported that an important increment at CHF value and quenching time was decreased with repeating tests.

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Fan et al. [8] carried out a quenching process with using nanofluids around copper spherical surface. They stated that the deposited particles on the heater surface caused increment wettability and by this effect CHF was increased significantly. Kim et al. [9] examined quenching process around steel spherical surfaces. As the coolant, composed with alumina nanoparticles and deionized water was used in their study. The researchers observed the transition of film boiling to transition boiling regime was rapidly after repetition tests. In addition, they stated a significant increment at MHF especially fourth repetition of tests.

Habibi et al. [10] investigated quenching performance with using carbon nanotube (MWCNT) nanofluids around silver spheres. They obtained lower CHF values at nanofluids. However cooling time was decreased both at pure water and nanofluids after repeated quenching experiments in their study. In the literature, studies on the quenching process are usually in cylindrical or spherical materials were used. But the results are conflicting.

This study is aimed to determine the best coolant for the quenching process among water-based silica, alumina, titania and copper oxide nanofluids (0.1 vol %) at atmospheric pressure and saturated conditions.

II. Experimental Setup

The nanofluids were generated using the two step method, which was shown in Fig. 1. SiO_2, Al_2O_3, TiO_2 and CuO nanoparticles that purchased from a company (NanoAmor©, Huston, TX, USA) were dispersed into pure water (0.1 vol %). The related mass fraction was determined by the following conversion formula [11].

$$\varphi_V = \left[\left(\frac{1-\varphi_m}{\varphi_m} \right) \frac{\rho_P}{\rho_f} + 1 \right]^{-1} \tag{1}$$

where φ_v and φ_m are the volume and mass concentration of nanoparticles, ρ_p is the nanoparticle density and ρ_f is the fluid density.

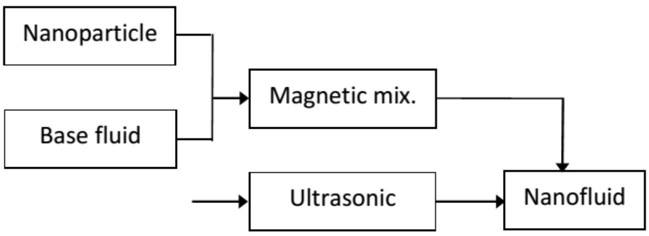

Fig. 1 Preparation process of nanofluid

To obtain homogeneous suspensions a magnetic mixer was used for 10 minutes at room temperatures. In order to prevent the nanoparticles sedimentation, ultrasonic vibration was applied to suspensions about 2h before the each test. The nanofluids prepared were shown in Fig. 2. After the preparation of nanofluid, thermal properties were determined by calculation. As shown in Table I, the thermal properties of the nanofluids were identical to pure water.

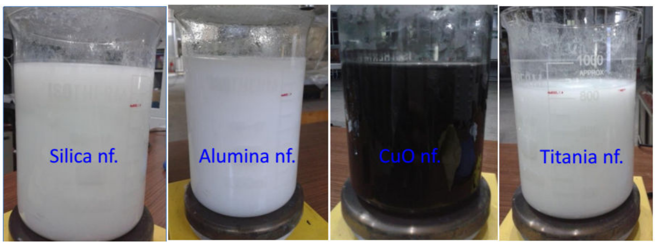

Fig. 2 The prepared nanofluids

TABLE I
THERMAL PROPERTIES OF THE BASE FLUID AND NANOFLUIDS

Fluid	Thermal properties			
	k_{nf} (W/mK)	μ_{nf} (Pa.s)	ρ_{nf} (kg/m^3)	$c_{p,nf}$ (J/kgK)
Pure water	0.613	1.370	997.1	4179
SiO_2 nf.	0.614	1.37	998.32	4175.57
Al_2O_3 nf.	0.648	1.42	1000.07	4175.59
TiO_2 nf.	0.620	1.38	1000.26	4175.53
CuO nf.	0.688	1.35	1002.41	4175.36

A schematic of the experimental apparatus used in this study is shown in Fig. 3. The main parts of experimental setup are a cylindrical furnace (diameter 400x200 mm), a pneumatic piston, a boiling vessel and a temperature measurement and recording system. As the test specimen, a brass sphere with a diameter of 10 mm was used. In order to measure the temperature of test specimen and furnace, K-type thermocouple was used. To obtain temperature data a 32-channel thermocouple amplifier was used and data was recorded with Genie Software. The specimen reached about 25 minutes from the room temperature to 600°C. The boiling vessel was placed on an external heater that heat capacity of 400 Watt (Yellow Line MSH Basic model). With this heater the pure water and nanofluids was reached to saturated temperature about 30 minutes.

Test specimen heated up to 600°C in the furnace when the nanofluids were heating in the boiling vessel up to boiling temperature. The experiments were carried out at saturated conditions (92°C) and under atmospheric pressure (~0.83bar). In order to reduce oxidation that may occur during the heating process nitrogen gas was given into the furnace. The specimen was suddenly immersed in the nanofluids when the specimen center temperature reached at 600°C. The center temperature-time values of specimen were recorded during the quenching period. The test ended when the specimen and nanofluid were thermal equilibrium. To determine the possible effects changing surface properties, quenching tests were repeated 5 times for same nanofluids without specimen polished. The test specimen polishing process was performed with emery papers (1200 mesh) and alumina slurry whenever nanofluid was changed.

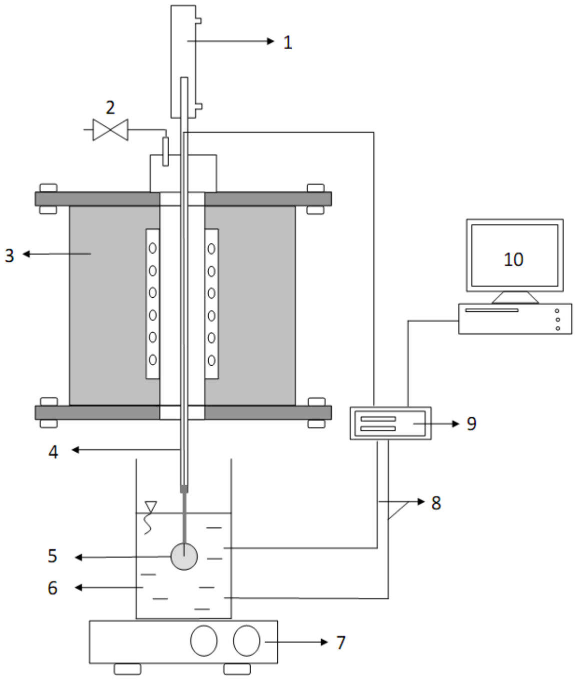

Fig. 3 Schematic of the experimental setup; 1- Pneumatic piston; 2- Nitrogen gas; 3- Furnace; 4- Support rod; 5- Specimen; 6- Quench pool; 7- Heater; 8- K-type thermocouple; 9- Analog-Digital Cart; 10- Computer

III. Results and Discussion

Fig. 4 shows the cooling curves of specimen that was cooled in pure water and nanofluids. As shown in Fig. 4, cooling curves are similar to pure water tests at first tests. This shows that, nanofluids have little or no effect on the polished test specimen. However, there is a shift in the cooling curves after first tests. As a result of repeated tests quenching curve to the left shift has been more pronounced. Thus, the film boiling ended sooner and the specimen cooled faster. Especially by repeated experiments there was not occurred a stable vapor film layer on the specimen surface for silica nanofluid.

The experimental results show that nanoparticle type has more effect on quenching behavior. Researchers have reported that accumulates of nanoparticles on the solid surface can change the surface morphology wettability [10]-[18]. If the surface is quite wetting surface, the liquid adheres on surface and spreads. In this case vapor film can collapse at high temperatures. By this effect cooling time can decrease.

Fig. 5 shows the sphere's surface photos for polished surface, after tests in pure water and nanofluids. As shown Fig. 5, there is a nonhomogeneous nanoparticle layer on the surface especially for silica nanofluid. It has been shown that changing of surface characteristics effect quenching period.

To verify this condition, the contact angles (θ) were measured from the surface of the test specimen for polished surface, quenched by pure water and SiO_2 nanofluids (*KSV, Cam-101* Scientific Inst.). While the contact angles for the surfaces polished and quenched by pure water were measured as 99.92° and 81.85°, respectively, it decreased up to 6.12° for the surface quenched by silica nanofluids. It is shown that the surface contact angle decreases significantly after the quenched by SiO_2 nanofluid. Consequently, the silica nanoparticles enhanced the performance of boiling heat transfer and it is the best coolant for the quenching among other nanoparticles.

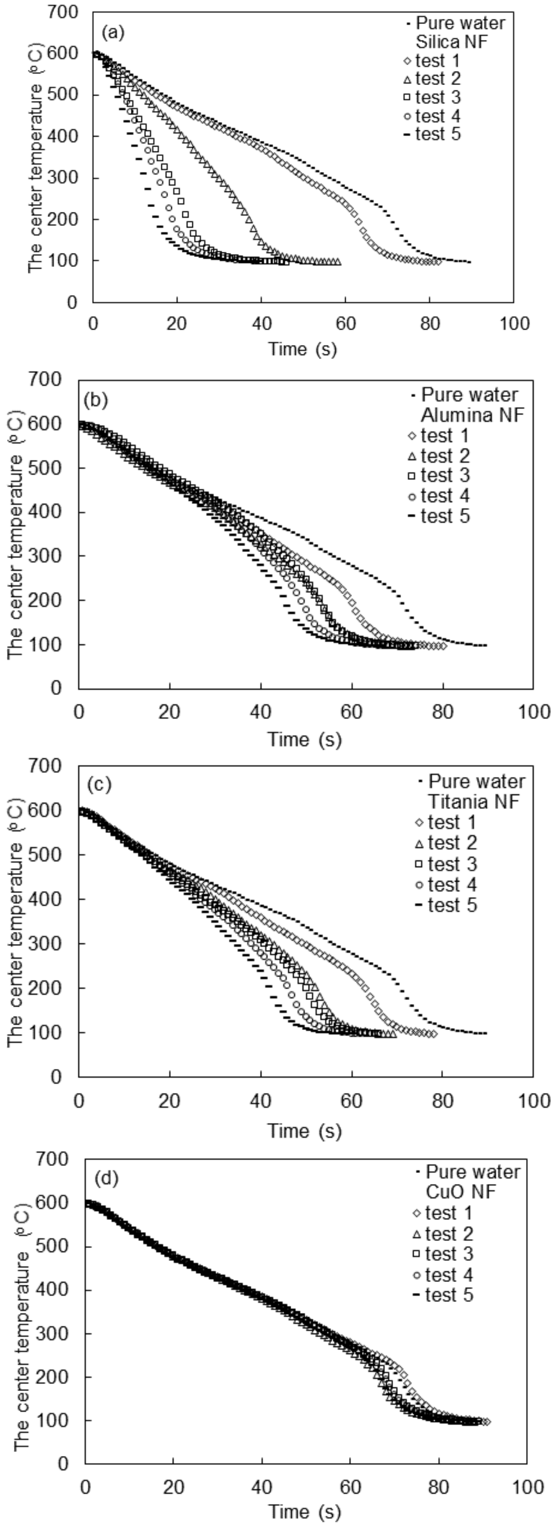

Fig. 4 The temperature-time values in nanofluids (0.1 vol%) at saturated conditions

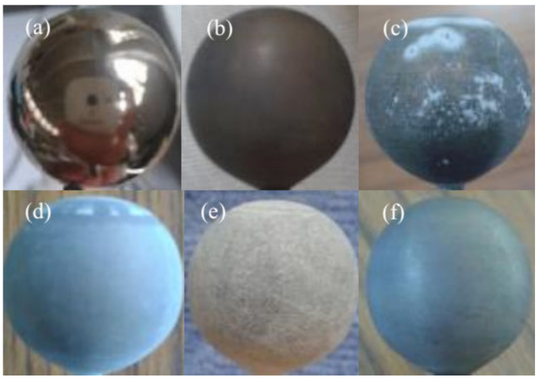

Fig. 5 Test specimen's photos (a) polished surface, after quenched by (b) pure water, (c) SiO_2, (d) Al_2O_3, (e) TiO_2 and (f) CuO nanofluids tests (0.1 vol%)

IV. Conclusion

The quenching behaviors of different nanofluids were experimentally investigated around a brass sphere. The nanofluids with 0.1 vol% particle fractions of silica (SiO_2), alumina (Al_2O_3), titania (TiO_2) and copper oxide (CuO) nanoparticles were prepared by two-step method. Test specimen was heated high temperature and then it was suddenly immersed into the nanofluid suspensions. By using the temperature-time data captured during the test, the cooling curves were obtained. The results showed that the type of nanoparticle used in nanofluids considerably affected the cooling process, especially with the silica nanoparticles. At the end of each test, it was observed a layer of nanoparticle on the test surface. The analysis of this layer showed a decrease in contact angle, therefore the fluid adhered on the surface and wetted more it. Therefore, the test specimen was cooled faster, especially in the case of SiO_2 nanoparticles. As a result, the silica nanofluid is the best coolant for the quenching process.

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