QUENCHING PERFORMANCE IN NANOFLUIDS AND NANOPARTICLES-DEPOSITED SURFACES

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ABSTRACT

Quenching experiments were conducted to investigate the effect of SiC and Graphene Oxide (GO) nanoparticles on the heat transfer during rapid cooling in vertical tubes. Temperature histories during the quenching were measured for each test section to confirm the effects of nanoparticles-coated layer and nanofluids on the quenching performance. The quenching time was decreased for nanoparticles-coated tubes about 20–31 % compared to bare tube. Also, SiC/water and GO/water nanofluid enhanced the quenching performance. Better quenching performance was observed for GO/water nanofluid compared to GO-coated tubes, while SiC/water nanofluid showed similar quenching performance with SiC-coated tubes. And scanning electron microscope (SEM) images of inner surfaces of tubes after experiments were acquired, and the contact angles were measured to observe the effect of surface structures and wettability on the quenching performance. In case of tubes coated with GO nanoparticles for 900 s, the quenching performance was enhanced although the contact angle increased. To confirm the surface effect on the enhanced quenching performance of GO-coated tubes, the FC-72 refrigerant was used as working fluid of quenching experiment to reduce the wettability effect on the heat transfer.

KEYWORDS
Quenching, Nanofluid, Nanoparticles-deposited surface, Crud

1. INTRODUCTION

Quenching phenomenon can be defined as rapid cooling of a hot object by a fluid such as water, ethylene glycol, oil, and so on. And the quenching process is one of the important issues for various engineering fields such as heat treatment of steel and safety of nuclear power plant [1]. The acceleration of the quenching process can ensure the safety of nuclear reactor when the emergency core cooling system (ECCS) operates at loss of coolant accident (LOCA) by lowering reflood peak cladding temperature. Many studies on the enhancement of quenching performance using various technologies have been under studying. And one of the technologies is nanofluid which is a type of heat transfer coolant that is made by dispersing engineered nanoparticles in conventional heat transfer fluids [2]. They show higher thermal performance than conventional fluids due to the suspended nanoparticles. Various nanofluids enhance pool boiling CHF due to porous structures, enhanced wettability, and thermal dissipation that the heat is dissipated through nanoparticles-coated layer by enhanced thermal effusivity

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[3]. These results demonstrate the potential applicability of nanofluids to the enhancement of quenching performance.

Kim et al. [4] studied experimentally the quenching for small metallic spheres exposed to pure water and Al_2O_3, SiO_2, diamond/water nanofluids at low concentrations. This study found that suspended nanoparticles in the nanofluids have no major effect on the quenching process. However, some nanoparticles deposit on the sphere surface during the quenching process can greatly accelerate the end of film boiling. Hence, they stated that the increase of surface roughness and wettability may be responsible for the earlier rupture of the vapor film which results in the acceleration of quenching process. Chun et al. [5] investigated the effects of Si and SiC nanofluids on a boiling heat transfer during a quenching of thin platinum (Pt) wire. They found that when the Si and SiC nanoparticle-coated Pt wires are quenched with the water, the nanoparticle-coated Pt wires are cooled down at a very high rate, compared to the bare Pt wires cooled by the water and the Si nanofluids. Bolukbasi and Ciloglu [6] studied the pool boiling heat transfer characteristics of a vertical cylinder quenched by SiO_2/water nanofluids. The authors found that the pool film boiling heat transfer in nanofluids is identical to that in pure water, but, during the repetition tests in nanofluids with high concentrations, the film boiling region disappears, and the critical heat fluxes increase. Lotfi and Shafii [7] performed transient quenching experiments on a high temperature silver sphere in Ag, TiO_2/water nanofluids to investigate boiling heat transfer characteristics of nanofluids. The initial temperature of test specimen was about 700 °C and the initial temperature of nanofluid was 90 °C. The authors found that the quenching process was more rapid in pure water than in nanofluids and the cooling time was inversely proportional to the nanoparticle concentration. They stated that nanoparticle deposition on the sphere surface acted as a thermal insulator for the sphere and reduced the temperature of the sphere outer surface, due to the higher thermal resistance of the TiO_2 layer. Also, nanoparticle deposition prevented a stable vapor film from forming around the sphere, which promoted the rapid quenching of the hot sphere. Kim et al. [8] studied the quenching characteristics of metallic rodlets and spheres in pure water and Al_2O_3/water nanofluids of 0.1% by volume. The experiments were performed in both saturated and subcooled conditions under atmospheric pressure. The authors found that the initial quenching behavior in nanofluids is identical to that in pure water, and the quench front speed is significantly enhanced in subsequent quenching repetitions due to nanoparticle deposition. They stated that the hydrophilic nature of the nanoparticle increases the area of the liquid–solid contacts during film boiling, which efficiently destabilizes the vapor film at higher temperatures and the very fast propagation of the quench front is also associated with local liquid–solid contacts during film boiling. The studies on the quenching performance using nanofluids concluded that there is no meaningful difference between nanofluids and water. However, the nanoparticle-coated surface of test section enhances the quenching performance due to earlier end of film boiling. Lee et al. [9] conducted the reflood heat transfer experiments to investigate the effect of 0.1 volume fraction (%) Al_2O_3/water nanofluid and carbon nano colloid (CNC) in the tube (1,000 mm in the heating length). The authors showed that the cooling performance is enhanced by more than 13 seconds and 20 seconds for Al_2O_3/water nanofluid and CNC, respectively. They concluded that a more enhanced cooling performance is attributed to a high wettability of a thin layer formed on a heating surface by a deposition of nanoparticles and the thin layer deposited nanoparticles is formed because the vapor including nanoparticles is deposited on heating surface before fluids are moved, when fluids are moved from bottom to top during reflood. Also, they concluded that a more enhanced cooling performance can be achieved by decreasing the amount of hydrogen at the severe accident

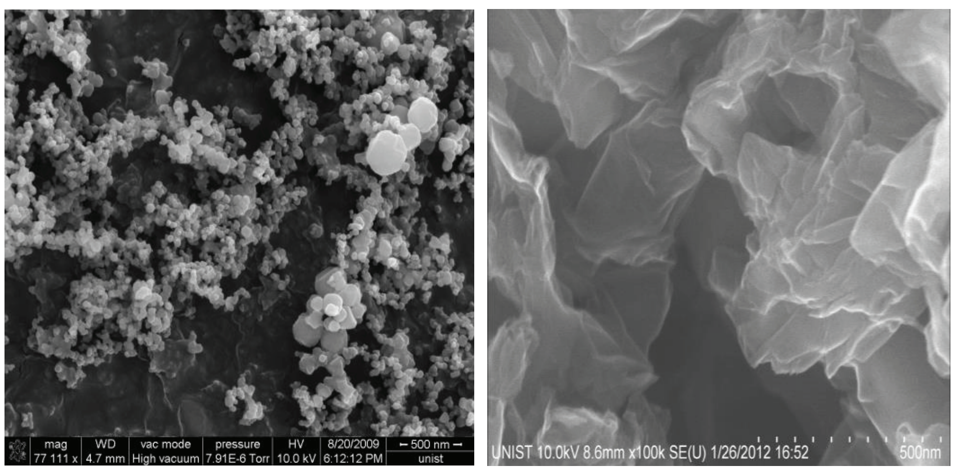
Thus, we conducted experiments with long vertical tube to observe the effect of nanoparticle-coated surface and nanofluids on the quenching performance. The nuclear fuel cladding tends to be rapidly oxidized during operation. But, the consideration of oxidation effect can cause coupling of parameters that affect to enhancement of quenching performance. So, the cladding oxidation effect on the quenching performance is not considered to observe the effect of nanoparticle-coated surface on the quenching performance only. Also, the various surface morphologies are formed by nanoparticles-deposition. So, this work can be meaningful in understanding crud effect on the quenching performance.

2. EXPERIMENTS

2.1. Preparation of the nanofluids

Graphene oxide and SiC nanoparticles were coated on the test section in this study. Graphene is flat monolayer of carbon atoms tightly packed into a two-dimensional lattice which structure results in high thermal conductivity, electrical conductivity, and tensile strength. Graphene oxide nanoparticles were used to utilize the excellent thermal conductivity of graphene and to secure stable dispersion in water simultaneously. And the main element of GO nanoparticles is carbon which has low neutron cross section. Hence, the GO nanoparticles can be easily applied to the nuclear reactor environment [10]. The GO nanoparticles used in these experiments were prepared by chemical vapor deposition (CVD) method. SiC is a promising material from the viewpoint of high temperature applications requiring non-gradation of material properties due to its good resistance to high temperature and high radiation environment. Thus, SiC is a candidate for wall materials of a fusion reactor and cladding material for light water nuclear reactor [11]. Figure 1 shows SEM images of the prepared GO and SiC nanoparticles which will be coated on the test section. Hence, we prepared SiC/water and GO/water nanofluids by dispersing the weighed nanoparticles into water and then sonicate the mixture continuously for 3 h.

GO/water and SiC/water nanofluids were prepared in 0.01 volume fraction (%) without meaningful change of physical properties and with stable dispersions during a long period.



(a) (b)

Figure 1. SEM images of nanoparticles : (a) SiC and (b) GO.

2.2. Experimental setup and procedure

Figure 2 shows the reflood test facility [13]. The test facility comprises a working fluid tank which store the working fluid and attenuate the backpressure (pressure produced by difference in water height between working fluid tank and test section, and vapor pressure), a pump that circulate the working fluid from the working fluid tank to the test section, a flowmeter to confirm the mass flow rate of the working fluid, working fluid drainage, the test section, and two copper electrodes on the top and bottom of the test section that are connected to the power supply and heat the test section with the passing current. The stainless steel 316 L test section has sheath outer diameter of 1/2 in (10.41 mm inner diameter), and 1300 mm heating length. Ten K-type thermocouples (TCs) with a sheath outer diameter of 0.5 mm were installed on the test section surface with a constant distance (118.2 mm) from the bottom copper electrode to record the temperature histories according to height (the uncertainty of the thermocouples was ± 1 °C). We covered the test section with glass fiber insulator, which is a common insulation material.

The 0.01 vol% SiC/water and GO/water nanofluids were injected at 3 cm/s flow rate which is corresponding to the injection flow rate by emergency core cooling system under a typical LOCA condition into preheated test section (600 – 650 °C) to deposit the nanoparticles on the inner surface of the test section. The quenching experiments were conducted with test sections at temperature ranges of 620 – 720 °C. The quenching method is used similarly to deposit the nanoparticles on the test surfaces and thus the preheating temperature was set to the experimental condition. The circulation of nanofluids last during 600 and 900 s to observe the coating time effect on the quenching performance. The boiling process induces the nanoparticle-coating on the test section. The nanoparticles are concentrated at the liquid sublayer which is located at vapor curvature during vapor growth. And the repulsive force which is induced by vapor departure from the surface results in the deposition of nanoparticles on the heater surface. And the adhesion force is significant to maintain the deposition of nanoparticles on the surface against the flow of water.

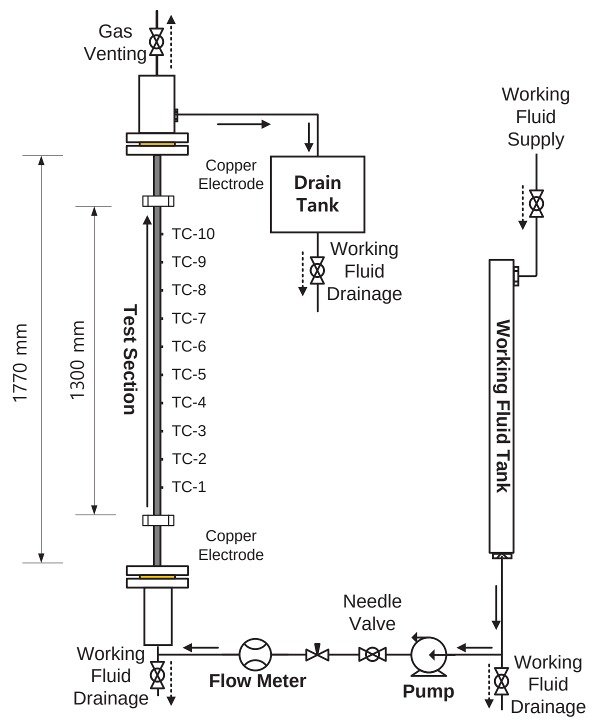


Figure 2. Schematic diagram of quenching experimental setup [11].

The quenching experimental procedure is as follows. The test section is heated to 620 – 720 °C (standard TC is second TC from the bottom; this is heated up to almost 720 °C), and then working fluid (water, SiC/water nanofluid, and GO/water nanofluid) of 25 °C from the working fluid tank is injected to the test section by the pump. When the water fills the below chamber fully, the DC power supplied to the tube is switched off. The injection flow rate (3 cm/s) is controlled by the pump and needle valve upstream of the test section. The flow rate of working fluid is injection flow rate of ECCS at LOCA in nuclear power plant. The uncertainty of the flow rate is less than 5 %. And the pressure drop during the injection of water into test section is minimized by the needle valve. Thus, the pressure drop can be ignored. The temperature histories were acquired and recorded by data acquisition system. The experiments were performed three times for each test section (bare tube and nanoparticle-coated tubes).

3. RESULTS AND DISCUSSIONS

3.1. Temperature histories

The cooling curves showed three different slopes as shown in Figs 3 – 5. The first boiling mode is film boiling where heat transfer occurs through a vapor film (slope that before dramatic temperature decrease). When the temperature reaches the Leidenfrost point (LP) temperature, the slope of the cooling curve changes dramatically, which mean transition boiling and nucleate boiling sequentially occur. The second change in the slope of the cooling curve signaled onset of single phase cooling [14].

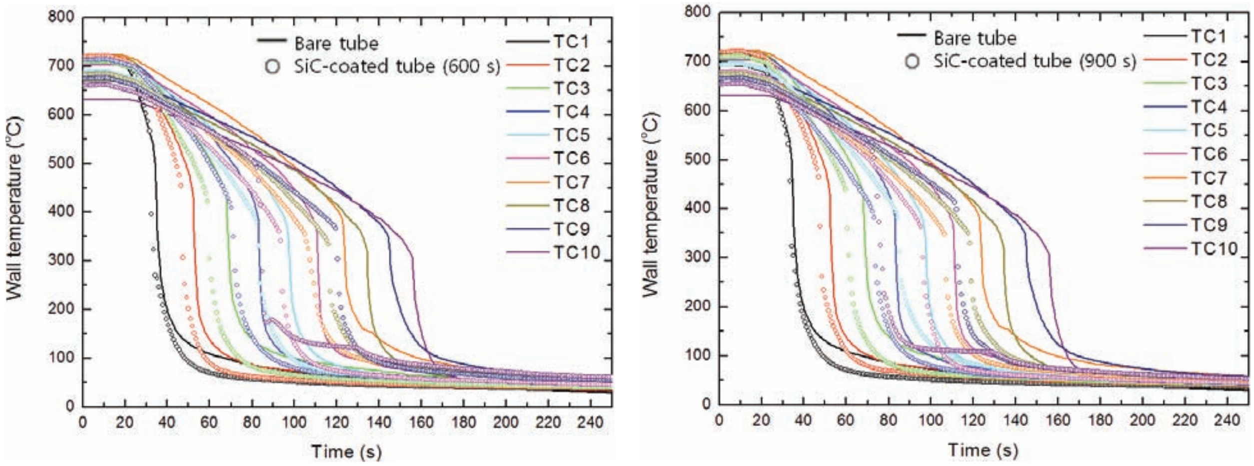
The repetition of the experimental results was ensured by conducting experiments three times for each test section. As shown in Figs. 3 – 5, the cooling curves of TC-1 showed no significant differences between bare tube and nanoparticles-coated tubes. However, the cooling performance was enhanced as the TC position increased from TC-2 to TC-10. The quenching process can be divided into two different mechanisms: bottom quenching and top quenching. The bottom quenching mechanism involves wetting the tube with liquid. In contrast, the top quenching process occurs by vapor condensation at the top of the tube. There are outlets for gas venting and working fluid drainage as shown in the Figure. 2. The vapor is condensed due to the heat transfer between cold air and vapor on the top through the outlets. If the vapor pressure produced by bottom quenching decreased, the condensed vapor on the top chamber would flow down to quench the test section. The rapid bottom quenching of nanoparticles-coated tube results in faster start of single-phase convection. Thus, the vapor pressures of nanoparticles-coated tube or nanofluids are decreased more rapidly than that of bare tube. As a result, The tubes coated with nanoparticles showed the top quenching process: i) For SiC nanoparticles-coated tubes and SiC/water nanofluid, the temperature at TC-10 decreased faster than at TC-5 to TC-9, ii) For GO nanoparticles-coated tubes and GO/water nanofluid, the temperature at TC-10 decreased faster than ones at TC-8 and TC-9. As shown in Figs. 3-5, the nanoparticles-deposited surface and nanofluids promote condensation.

The quenching time and velocity for each tube were measured. In the experiments, the quenching time was calculated from the difference in quenching time at the most slowly quenched position and the time at the location of TC-1 (i.e., the most rapidly quenched position). The quenching velocity was found by dividing the length interval between TC-1 and the most slowly quenched position by the calculated quenching time.

The average quenching time and velocity of the bare tube were 122.41 s and 0.87 cm/s with a maximum deviation of 0.2 %. The quenching time for the tube coated with SiC for 600 and 900 s were 32 s (26 %) and 38 s (31 %) shorter than that of the bare tube as shown in Table 1. The tubes coated with GO nanoparticles for 600 and 900 s showed quenching times that were 23 and 25 s (about 20 %) faster, respectively, that the quenching time of the bare tube. The uncertainty of the quenching time and velocity was within 2.7 %. Also, SiC/water nanofluid and GO/water nanofluid showed faster quenching velocities than water. Especially, SiC-coated tube and SiC/water nanofluid showed similar quenching performances although GO/water nanofluid showed better quenching performance than GO-coated tube. Thus, the more dominant effect of hydrodynamics on the quenching can be confirmed with GO/water nanofluid.

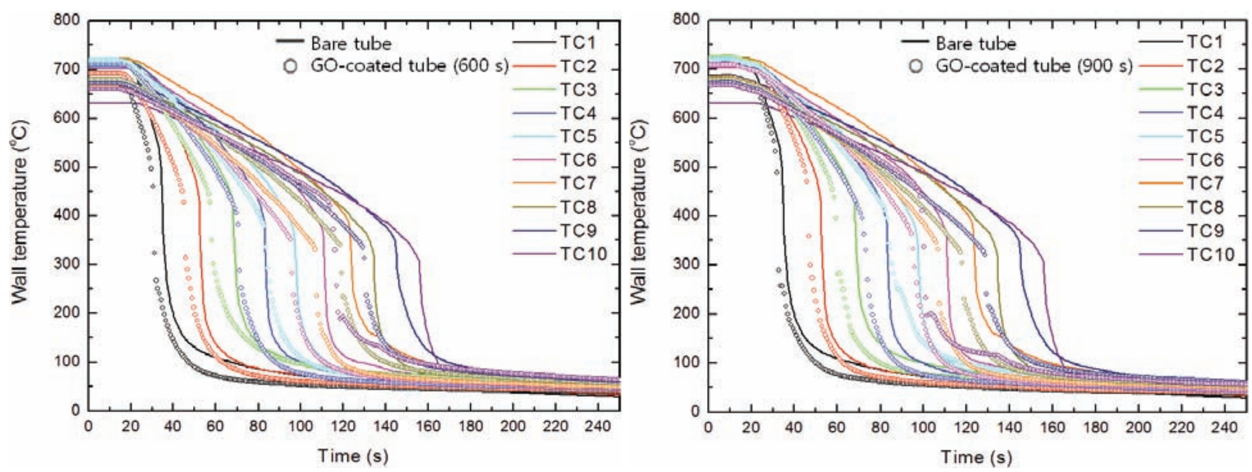
Table 1. Comparison of quenching velocity according to working fluids and test sections

Test section	Average quenching time (s)	Distance from TC-1 to TC-9 or TC-10 (cm)	Average quenching velocity
Bare tube	122.41	106.2	0.87
SiC-coated tube (600s)	89.33	94.4	1.06
SiC-coated tube (900s)	83.97	94.4	1.12
GO-coated tube (600s)	99.59	99.4	1.00
GO-coated tube (900s)	97.05	99.4	1.02
SiC/water nanofluid	88.94	99.4	1.11
GO/water nanofluid	90.52	99.4	1.09



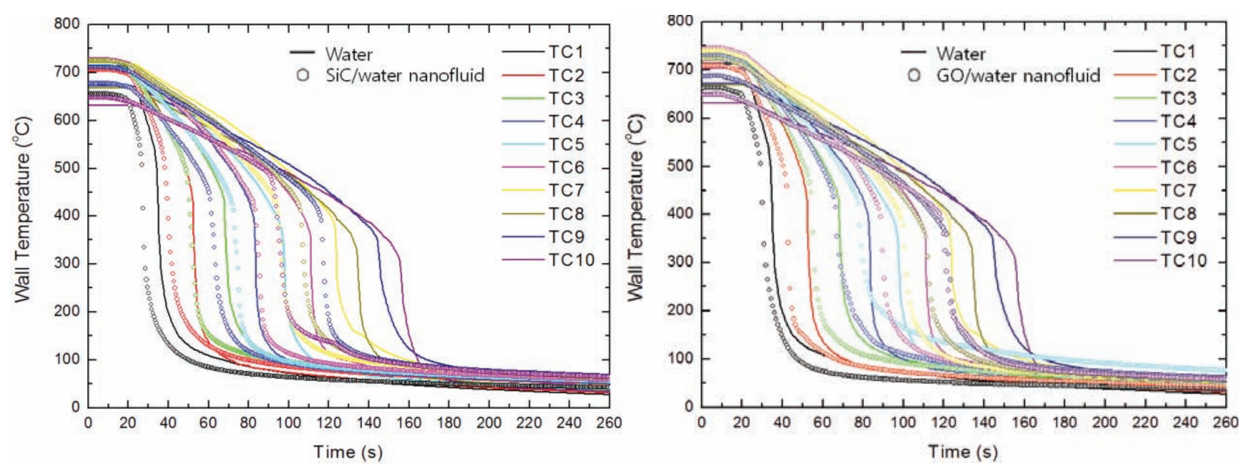
(a) SiC-coated tube (600 s) (b) SiC-coated tube (900 s)

Figure 3. Temperature histories of SiC-coated tube and bare tube during quenching.



(a) GO-coated tube (600 s) (b) GO-coated tube (900 s)

Figure 4. Temperature histories of GO-coated tube and bare tube during quenching.



(a) SiC/water nanofluid (b) GO/water nanofluid

Figure 5. Temperature histories of SiC/water nanofluid and GO/water nanofluid during quenching.

3.2. Leidenfrost temperatures

Leidenfrost point (LP) temperatures which are the temperature points that slopes of cooling curve change dramatically were also measured for each test.

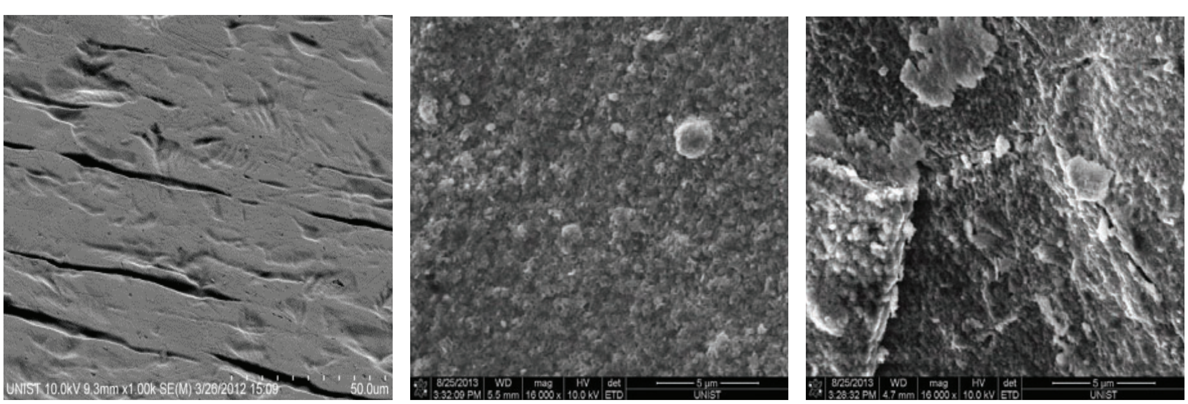
Table 2. Leidenfrost point (LP) temperatures for each test section

Test section	Average LP temperature (°C)
Bare tube	305.1
SiC-coated tube (600s)	365.4
SiC-coated tube (900s)	389.4
GO-coated tube (600s)	321.5
GO-coated tube (900s)	323.2
SiC/water nanofluid	390.9
GO/water nanofluid	358.6

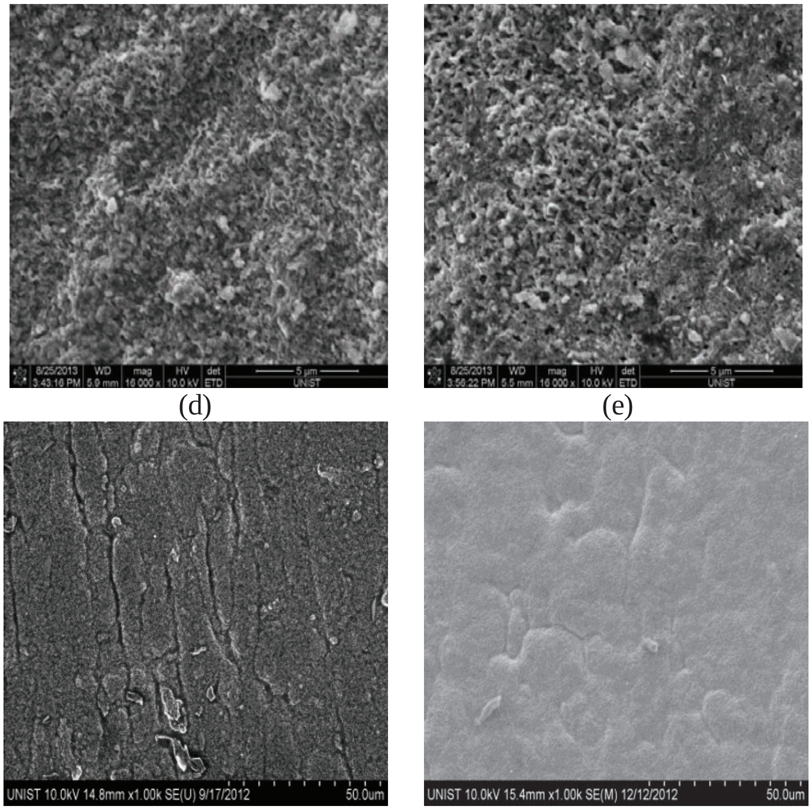
Table 2 shows the minimum LP temperatures for each test. The LP temperature defined in this work is the minimum quench temperature among the TC locations (The most slowly quenched location). As the Leidenfrost point temperature increases, the vapor film is ruptured earlier, and transition boiling heat transfer occurs, which decreases the quenching time [15]. Hence, the peak cladding temperature decreases by the amount of heat generated during the decreased quenching time. As shown in Table 2, LP temperature is proportional to the quenching time of the tests.

3.3. Surface structures and contact angles

In order to observe effects of the surface structures and wettability on the quenching performance, the inner surface of the test section was analyzed. The inner surfaces of tubes which were analyzed are parts that located at TC-2. And the contact angles according to different locations are similar with the results shown in TC-2 position with maximum deviation of 4.4 %. The SEM images of Figs. 6(b) and (c) show that the SiC nanoparticles were deposited on the inner surface of the tubes. Figure. 6(a) shows the bare tube. The layer of GO nanoparticles forms a porous structure as shown in the Figs. 6(d) and (e). Also, the test sections tested with SiC/water nanofluid and GO/water nanofluid showed nanoparticles-deposited layer. However, the test section quenched by GO/water nanofluid did not show the porous structure like GO-coated surfaces for 600 and 900 s.



(a) (b) (c)



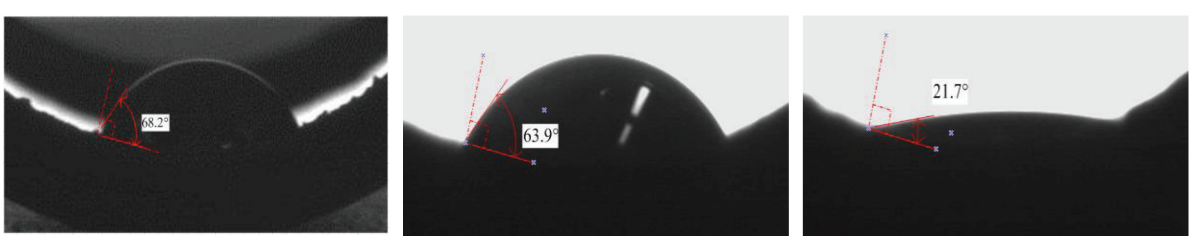
(d) (e)

(f) (g)

Fig. 6. SEM images of inner surfaces of test sections after reflood tests: (a) bare tube, (b) SiC-coated tube (600 s), (c) SiC-coated tube (900 s), (d) GO-coated tube (600 s), (e) GO-coated tube (900 s), (f) SiC/water nanofluid and (g) GO/water nanofluid.

The contact angle in the inner surface of the bare tube was 68.2°. As shown in Figure. 7, for SiC nanoparticles the contact angle measured after the reflood experiments decreased with the coating time. The test section quenched with SiC/water nanofluid shows reduced contact angle. Hence, the wettability was increased with the SiC nanoparticle deposition. Thus, the cooling performance was enhanced by the increased wettability due to SiC nanoparticles deposition on the tubes. Tubes showed enhanced wettability when coated with GO nanoparticles for 600 s and GO/water nanofluid was used. However, the contact angle on the inner surface of tube coated with GO nanoparticles for 900 s was 71.8° despite the enhanced quenching performance. Hence, surface modifications such as roughness and a porous structure contribute to the enhanced quenching performance of tubes coated with GO nanoparticles.

While the nanoparticles-coated tubes show similar surface structures, the SiC-coated tubes showed better wettability in comparison with GO-coated tubes. Thus, the better quenching performance was acquired at SiC-coated tubes compared to GO-coated tubes. However, further investigation of detailed inner structures of coated surfaces should be considered for clear reasoning.



(a) (b) (c)

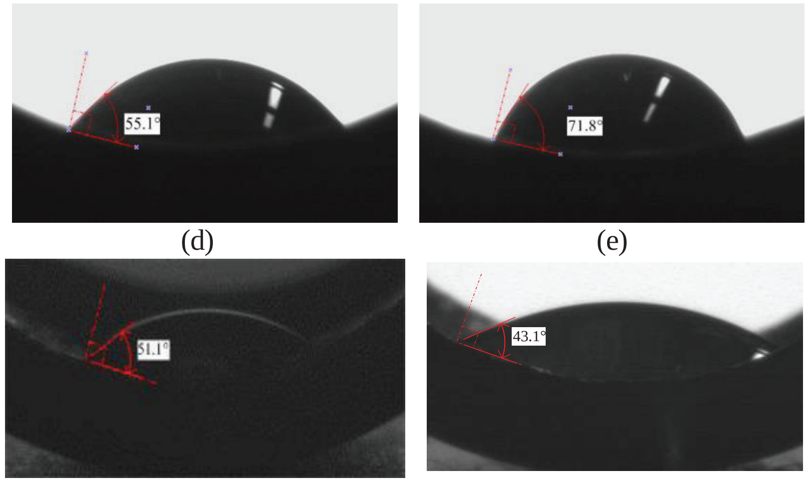


Fig. 7. Contact angles of the inner surfaces of test sections after reflood tests: (a) bare tube, (b) SiC-coated tube (600 s), (c) SiC-coated tube (900 s), (d) GO-coated tube (600 s), (e) GO-coated tube (900 s), (f) SiC/water nanofluid and (g) GO/water nanofluid.

3.4. FC-72 Quenching

The enhanced quenching performances in GO-coated tubes resulted from the effect of porous surfaces as discussed in previous sections. However, the porous effect should be confirmed by minimizing the effects of wettability and roughness on the quenching heat transfer. Thus, FC-72 refrigerant was used as working fluid in GO-coated tubes due to its good wetting property. But, latent heat of the FC-72 (88 kJ/kg) is lower than that of water (2248 kJ/kg). So, each test section was preheated to 400 °C. And the remaining experimental procedures are same with those of water quenching experiment. Figure8 shows the quenching performance in GO-coated tubes were enhanced about 25 % compared to that of bare tube. And there was no significant difference in quenching performances as increasing nanoparticle coating time. The result confirms the effect of porous surface on the quenching heat transfer. The porous surface induces capillary flow that can supply liquid to the heater surface rapidly resulting in the higher evaporation rate. It means that the effective rewetting front propagating on the heater surface can be faster due to the capillary flow. Thus, the quenching heat transfers were enhanced in GO-coated tubes.

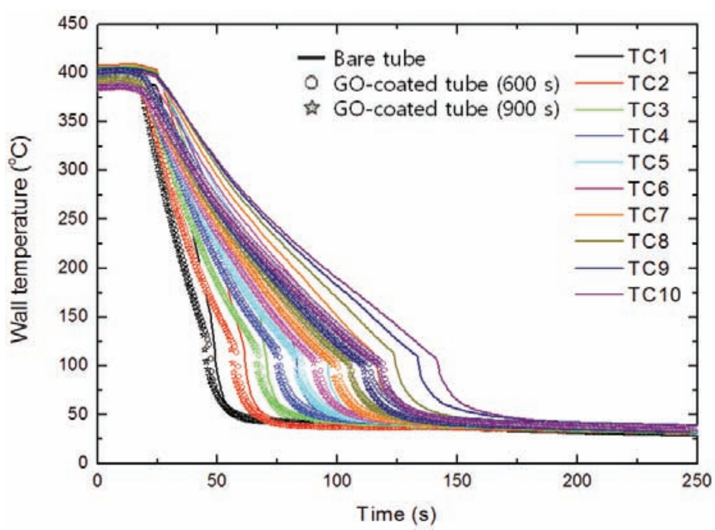


Fig. 8. Temperature histories during FC-72 quenching for each test section.

4. CONCLUSIONS

In this study, we examined the effect of nanoparticle deposition in a long vertical tube on quenching performance and CHF.

The following results were obtained.

(1) The reflood tests were performed using water in a bare tube and tubes coated with SiC nanoparticles. The latter showed a more enhanced cooling performance.

(2) For the tubes coated with SiC nanoparticles and quenched by SiC/water nanofluid, the enhanced quenching performance was attributed to the high wettability of the thin layer formed on the heating surface by nanoparticle deposition. The thin layer and enhanced wettability were confirmed by SEM and observation of the contact angles of the inner surface of the tubes.

(3) The enhanced quenching performance of tubes coated with GO nanoparticles was due to the rough and porous structure of the coating layer of GO nanoparticles in the tube. And the porous surface effect on the quenching heat transfer was confirmed by FC-72 quenching experiment.

(4) The cooling performance was enhanced with increased nanoparticle coating time.

(5) The SiC/water nanofluid and SiC-coated tubes showed similar quenching performance confirming the enhanced quenching of nanofluid results from the nanoparticles-deposited layer.

(6) The GO/water nanofluid showed better quenching performance than GO-coated tubes. So, further study on the hydrodynamic effect of GO/water nanofluid is necessary.

The nanoparticles effects also can be useful in understanding effects of crud for quenching.

ACKNOWLEDGMENTS

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