EXPERIMENTAL INVESTIGATION OF CRITICAL HEAT FLUX ON SiO_2 THIN FILM DEPOSITED COPPER SUBSTRATE IN DI WATER AT ATMOSPHERIC PRESSURE

by

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High heat flux at low excess temperature is the prime factor in pool boiling heat transfer. One of the methods to enhance peak heat flux in nucleate boiling is surface modification. The substrate of the copper has been modified by SiO_2 thin film coating. The coating was performed on the substrate at three different thicknesses 250 nm, 500 nm, and 750 nm. The thin film coating was done by sputtering technique. The water contact angle was measured for bare and SiO_2 thin film coated substrates. The contact angle decreased drastically because of more nucleation sites involved for wetting the substrate. The coating characteristics reported that the wettability of the copper substrate plays an important role in the critical heat flux enhancement. The critical heat flux test was carried out for bare copper substrate and SiO_2 thin film coated copper substrates. The SiO_2 thin film coating exhibited superhydrophillic nature on the substrate because of greater wettability. The superhydrophillic nature of the substrate enhanced the peak heat flux significantly. Also the boiling heat transfer coefficient was improved at high heat flux in nucleate boiling regime.

Key words: *pool boiling, critical heat flux, wettability, thin film coating, heat transfer coefficient*

Introduction

The cooling of electronics components and nuclear reactor cooling are very important in thermal management system. The rate of cooling in multiphase heat transfer is expected to be efficient. In pool boiling heat transfer the critical heat flux plays a vital role. The achievement of high critical heat flux at low wall superheat provides better life of multiphase heat transfer equipment. Gouda *et al.* [1] compared the heat transfer performance of segmented fin configuration in micro-channels with bare substrates and micro-channel with uniform cross-section. The results showed that the enhancement in heat transfer achieved significantly for segmented fin configuration substrates due to better wetting over the substrate. Seo *et al.* [2] investigated the nucleate boiling heat transfer over the surfaces provided with holes of different patterns. Indium tin oxide layer was used as heater material. They reported the CHF and BHT enhanced significantly than the plain surface due to rewetting concept. Jo *et al.* [3] found enhancement in critical heat flux of the surface modified by micro-pillars of different sizes. The modification was done on copper substrates by spraying copper micro-particles supersonically

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through a mesh of wire. Kim *et al.* [4] prepared copper surfaces by polytetra fluoroethylene coating and reported the enhancement of boiling heat transfer coefficient. The results showed roughness of the surfaces induced good wetting over the surfaces which lead to significant heat transfer. Kumar *et al.* [5] achieved 60% enhancement of critical heat flux and 300% boiling heat transfer than the polished copper substrates due to more nucleation sites on the modified surface. Ganesan *et al.* [6] investigated the pool boiling heat transfer over the surface patterned by seamless graphene-CNT. The results indicated the enhancement observed due to rewetting characteristic performed on the modified surface. Voglar *et al.* [7] showed that numerous active nucleation sites caused the significant improvement in peak heat flux. The nucleation sites are developed by creating cavities in microns by laser texturing on surfaces. The size of the cavities ranges 0.2-10 μm in diameter. The CHF enhanced 3.7 times higher than that of plain surface. Avudaiappan *et al.* [8] said critical heat flux was enhanced at high surface temperature because of hydrophillicity. Holguin *et al.* [9] conducted investigations for dielectric fluid on copper surface modified as binary surfaces. The peak heat flux was observed 2.2 times and heat transfer coefficient enhanced by 7.5 times. Vivekanandan *et al.* [10] investigated the heat transfer characteristics of TiO_2 nanostructured surfaces at various thicknesses. The electron beam evaporation technique was adapted for coating and they reported the significant enhancement in heat transfer due to the greater wettability achieved on the substrate. Saravanan *et al.* [11] conducted experiments in pool boiling in water on porous surfaces. The critical heat flux enhancement was achieved significantly because of liquid entrainment due to capillary wicking characteristics. Jaikumar, *et al.* [12] investigated heat transfer for the surfaces coated by carbon which was more conductive and graphene oxide. They reported the enhancement maximum to 192 W/cm^2 than the ridge microstructures made on the surface. An *et al.* [13] showed the improvement in wettability of reduced graphene oxide and significant improvement in critical heat flux due to roughness created the more nucleation sites. The nucleation caused better liquid mixing and lead to small scale bubble formation. The proposed study reveals that the nucleate boiling heat transfer on SiO_2 thin film coated copper substrates with three different coating thicknesses. In this present work, the sputtering technique is adopted and heat transfer investigations are carried out. The sputtering technique offers high strength coating and better binding energy between copper substrates coating material.

Methodology

Deposition of thin film

The copper substrate of 3 mm thickness and 10 mm diameter were taken for the nucleate boiling experiment. The sputtering technique was employed for coating SiO_2 thin film on the pure copper substrate in sputtering machine (PLASSYS MP 300, France). The following steps were carried out during thin film deposition process. Initially the SiO_2 target was mounted on the holder in the coating chamber. Copper specimen was prepared by emery sheets of 1000 G and cleaned by acetylene to remove dusts and impurities present on the surface. The polished copper substrate was mounted on workplace in the chamber. The power of 100 W was selected for SiO_2 target and all the SiO_2 particles in nanosize were deposited during the coating process. The vacuum pump and diffusion pumps were employed for maintaining vacuum inside the chamber. The thin SiO_2 film was grown on the surface slowly and the thickness were controlled by varying the coating duration. The thickness monitoring indicator in the sputtering machine was used for measuring the thickness of film. The deposition time for 250 nm, 500 nm, and 750 nm were approximately 35, 62, and 94 minutes, respectively.

Surface characterisation techniques

The characterisation SiO_2 thin film coated surfaces were studied by different techniques. First, the water contact angle of the bare substrate was tested and similarly all the SiO_2 thin film coated surfaces were measured by water contact angle goniometer (KRUSS GmbH-FM40Mk2, Germany). In the sessile drop method the water droplet of 3 µL were used for testing. The surface morphology was studied with results from SEM. The surface roughness was studied on the thin film deposited surfaces. The structural properties were studied by the results from X-ray diffraction measurement technique (PANALYTICAL-X'PERT, Netherland).

Experimental set-up

The pool boiling experimental set-up shown in fig. 1 consists of boiling chamber, main heater, auxiliary heater, K-type thermocouples, copper block, power supply unit, data acquisition system, pressure gauge, chiller unit, and reflux condenser. The copper specimen was fixed on the top of the copper block with thermal paste. The copper block accommodated four cartridge heaters of 250 W each. The entire copper block was covered by glass wool to ensure 1-D heat conduction in axial direction. The copper block was machined to accommodate three thermocouples and one thermocouple inserted at copper specimen. The boiling chamber was filled with de-ionized (DI) water and the auxiliary heater was used to maintain the temperature of DI water at saturation state. Another thermocouple was used in the boiling chamber to measure the temperature of water. The reflux condenser was made as a coil which was inserted into the chamber to cool the water vapour evaporated from the chamber during boiling process. The hot water from the condenser is cooled down by chiller unit available in the pool boiling set-up.

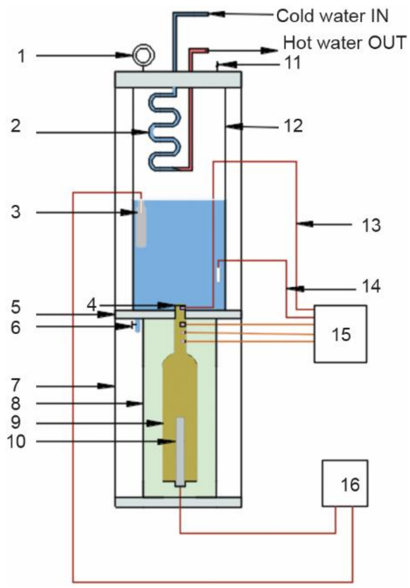

Figure 1. Schematic illustration of pool boiling experimental set-up; *1 – pressure gauge, 2 – reflux condenser, 3 – auxiliary heater, 4 – test surface, 5 – teflon insulation surface, 6 – drain valve, 7 – rigid stand, 8 – glass wool insulation, 9 – heater block, 10 – main heater, 11 – pressure relief valve, 12 – pool boiling chamber, 13 – thermocouple for test specimen, 14 – thermocouple for water, 15 – data logger, 16 – power supply unit*

The pressure gauge was used to measure the pressure inside the chamber and pressure relief valve mounted on chamber to release the excess pressure of water vapour. The upper and lower portion of the chamber was separated by Teflon base for providing better insulation. The thermocouples were connected to the data acquisition system to read the temperatures at every moment. The heat inputs to the heaters are adjusted by power supply unit. Initially, the experiment was run for five hours to remove non-condensable gases. Then the heat input was adjusted to raise the heat flux. Once the system reached steady-state condition, the heat flux and heat transfer coefficient were calculated. The heat flux was calculated up to the regime of boiling reached the peak heat flux. The peak heat flux point has been attained by observing the temperature jump to higher value in very short period. In this burnout point the heat flux to heater block was stopped. The experiment was run for all SiO_2 thin film coated surfaces of three different thicknesses.

Results and discussions

Effect of wettability

The wettability is one of the prime factors in nucleate boiling heat transfer. The more wetting behaviour of the surface exhibits hydrophillic nature. The water contact angle of the surface determines the wettability. In the present work, the water contact angle of the bare copper substrate and SiO_2 thin film coated substrate were measured. The contact angle of the bare copper substrate read at 83^o followed by thin film coated substrates were read 28^o, 25^{o,} and 15^o for 250 nm, 500 nm, and 750 nm thick surfaces, respectively, shown in fig. 2. The contact angle of 750 nm coated substrate exhibited more wettability than other surfaces. The surface energy of the thin film coated substrates increased and produced more wettability on the surface and these surfaces are called superhydrophillic surfaces. The numerous nucleation sites are created due to this nature. Also the surface area becomes large due to more nucleation sites and more wetting caused the enhancement in boiling heat transfer.

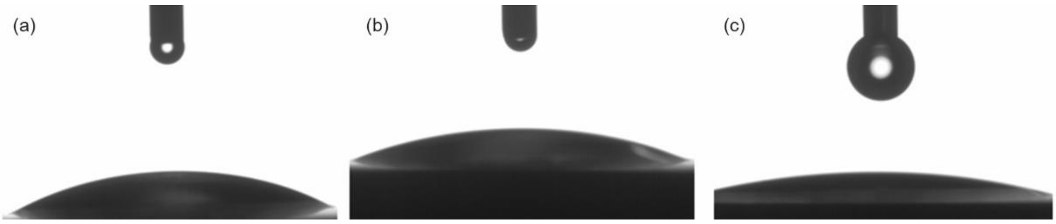

Figure 2. Contact angle of SiO_2 thin film coated copper substrates for; (a) 250 nm thickness, (b) 500 nm thickness, and (c) 750 nm thickness

Surface roughness analysis

The surface roughness plays a vital role in pool boiling heat transfer investigations. The surface roughnesses of the thin film coated substrates were measured by stylus profilometer (Bruker). The results showed that 250 nm SiO_2 coated surface was read at 0.145 μm and 500 nm SiO_2 copper substrate was read at 0.153 μm and for 750 nm was 0.328 μm. More roughness values provided more nucleation sites on the boiling surface. The tendency of increasing roughness enhanced the wetting and rewetting characteristics of the substrate. The more voids on the surface and increased surface area offered better mixing of boiling liquid and caused for liquid entrainment during nucleate boiling. These capillary wicking characteristics of the boiling surface enhanced the heat transfer further more.

Effect of surface characterisation

The morphology of the surface was studied on the thin film SiO_2 coated substrates. The SiO_2 coated surfaces were scanned by SEM. The SiO_2 thin film was spreaded uniformly on all the area of the surfaces at all thicknesses. The bonding between thin film and substrate were good and surface energy exhibited was good.

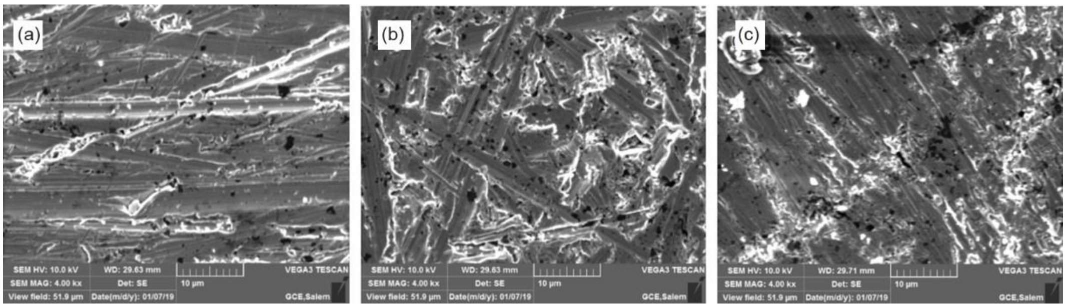

Figure 3. The field emission SEM images of SiO_2 thin film on copper substrates; (a) 250 nm, (b) 500 nm, and (c) 750 nm

The adhesiveness of SiO_2 over the copper substrate found good and field emission SEM images shown in fig. 3 revealed that the numerous nucleation sites were formed on the sites. The more nucleation sites increased more surface area and good wetting property. The evidenced morphology of the SiO_2 thin film on copper substrate enhanced the critical heat flux and boiling heat transfer coefficient significantly. The X-ray diffraction spectrum in fig. 4 showed that the presence of SiO_2 on the copper substrates. The peaks were evidenced on the surface at 44.6° for SiO_2 thin film and another peak at 51.7° for copper substrate.

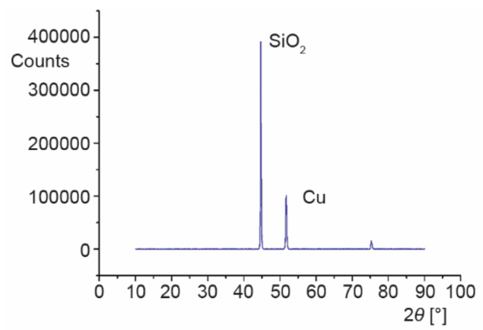

Figure 4. The XRD pattern of SiO_2 thin film coated surface

Boiling characteristics

The experimental results on heat flux of SiO_2 thin film coated substrates were analysed and these results have been compared with bare surface. The critical heat flux of the bare copper substrate was found at 123.8 W/cm^2. Since the contact angle of the SiO_2 thin film coated substrates are very low, the substrates offered more heat transfer area and especially enormous active nucleation sites. Initially the bubbles were formed in the nucleation sites at low wall superheat. At higher heat flux, bubble formation and detachment occurred in a rapid manner and system attained critical heat flux. The trend of increasing heat flux with increase in wall superheat occurred for all kind of surfaces in pool boiling heat transfer. From this investigation, it was observed that the critical heat flux for the thin film coated substrates increased substantially.

The critical heat flux for 250 nm coated substrate was found at 195 W/cm^2. The copper surface coated with 500 nm thick was observed at 221 W/cm^2 and for 750 nm was evidenced at 245 W/cm^2. The significant enhancement in critical heat flux was found in all SiO_2 thin film coated substrates. The trend of enhancement in critical heat flux with increasing thickness for all SiO_2 thin film surfaces were evidenced due to improved wettability, more surface roughness, extended heat transfer surface area and better surface morphological properties. The heat transfer enhancement was achieved 58 %, 79%, and 98% greater than that of bare copper substrate. The curves shown in the fig. 5 provided the information about the enhancement of heat flux with respect to wall superheat. The improvement in heat transfer surface area offered by the nucleation site and roughness of the surface exhibited good achievement in boiling heat transfer coefficient. The boiling heat transfer coefficient started to increase significantly after interface evaporation. This increasing trend occurred greatly up to the surface reaches critical heat flux regime. Due to more heat transfer area on the surface, the energy carrying fluid DI water transferred more heat than the bare substrate. The heat flux *vs.* heat transfer coefficient curves shown in fig. 6 revealed that the SiO_2 thin film coated copper exhibited better heat transfer. The various factors of sputtering technique produced thin film coating with good adhesiveness and excellent structural stability. The remarkable enhancement of critical heat flux and boiling heat transfer coefficient for SiO_2 thin film coating on copper substrate revealed best alternative for heat transfer applications like nuclear reactor, electronics cooling, *etc.*

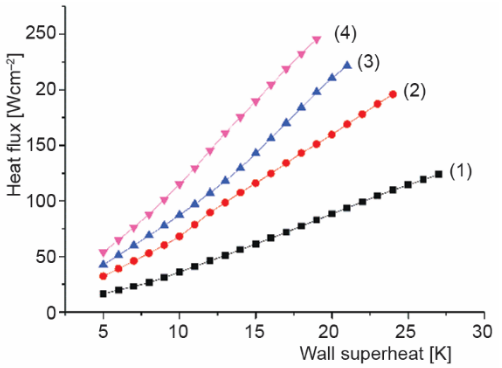

Figure 5. Heat flux variation with wall superheat; *1 – heat flux for bare copper substrate, 2 – heat flux for 250 nm thick SiO_2 thin film deposited copper substrate, 3 – heat flux for 500 nm thick SiO_2 thin film deposited copper substrate, 4 – heat flux for 750 nm thick SiO_2 thin film deposited copper substrate*

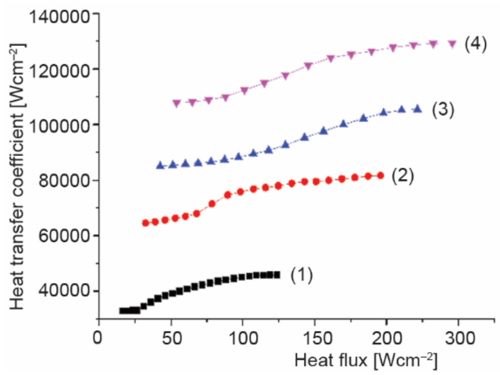

Figure 6. Heat transfer coefficient curve with heat flux; *1 – heat flux for bare copper substrate, 2 – heat flux for 250 nm thick SiO_2 thin film deposited copper substrate, 3 – heat flux for 500 nm thick SiO_2 thin film deposited copper substrate, 4 – heat flux for 750 nm thick SiO_2 thin film deposited copper substrate*

Bubble formation and detachment characteristics

In this work the bubble was formed on the SiO_2 thin film coated surface at 32.2 W/cm^2 for the wall superheat of 5 K and for thickness of the film was 250 nm. The bubble formed on the surface was detached from the surface and condensed in the DI water itself due to difference vapour pressure at the saturation temperature. The addition of heat input increased the bubble formation frequency and departure rate. At wall superheat 10 K the formed bubbles reached top surface the water and energy was transferred. The heat flux at this stage was evidenced 67.9 W/cm^2 and heat transfer coefficient was attained 67906 W/m^{2}K. The heat input for further added which in turn enhanced the critical heat flux and it was observed at 24 K. The same scenario was happened for all SiO_2 thin film deposited copper substrates. But the formation of bubble for 500 nm and 750 nm were happened at 42.5 W/cm^2 and 53.9 W/cm^2, respectively. The trend of increase in heat flux was happened for bubble detachment and also for reaching to top surface of fluid. The heat flux at 500 nm thick SiO_2 thin film coated was evidenced 87.2 W/cm^2. This enhancement was obtained 28% greater than that of 250 nm thick SiO_2 deposited substrate and 1.43 folds higher than that of bare copper substrate. The heat flux at burnout point was evidenced at 195.8 W/cm^2 for 250 nm thick SiO_2 deposited substrate, 221.4 W/cm^2 for 500 nm thick SiO_2 deposited substrate also evidenced at 245.6 W/cm^2 for 750 nm thick SiO_2 deposited substrate. This enhancement for 500 nm thick SiO_2 coated substrate was 13% higher than that of 250 nm thick SiO_2 coated surfaces and 79% greater than that of bare copper substrate. But the highest heat flux achieved for 750 nm thickness coated substrate was 25% higher than that of 250 nm thick coated and 11% greater than that of 500 nm thick SiO_2 coated copper substrate. This remarkable enhancement in critical heat flux and heat transfer coefficient is best suitable for multiphase heat transfer applications.

Conclusion

The SiO_2 thin film coating on the copper substrate was done by sputtering technique. The SiO_2 thin film deposited on the copper substrates at three different thicknesses are 250 nm, 500 nm, and 750 nm. The thickness of the coating was controlled by different parameters in the sputtering machine. The coating and surface characterisations were studied from field emission SEM and XRD techniques. The SiO_2 coated surfaces exhibited superhydrophillic nature due to enhanced wettability. The pool boiling investigations were conducted on the bare and SiO_2 thin film coated substrates. The critical heat flux and heat transfer coefficient of bare and SiO_2 thin film coated surfaces were analysed. The critical heat flux for 250 nm, 500 nm and 750 nm SiO_2 thin film coated substrates were found at 195 W/cm^2, 221 W/cm^2, and 245 W/cm^2. The critical heat flux was enhanced 58%, 79%, and 98% greater than that of bare copper substrate. The significant enhancement in critical heat flux and heat transfer coefficients offers best alternative for effective thermal management systems.

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