TABLE OF CONTENTS

Contents **Page**
No.

Certificate, Declaration and Copy right transfer ii-iv

Acknowledgement v-vi

Table of Contents vii-x

List of figures xi-xv

List of Tables xvi

List of symbols xvii-xx

Abstract xxi-xxiii

1. Introduction 1-10

1.1 Boiling curve and Regime of boiling 1

1.2 Nucleate boiling: the preferred regime 4

1.3 Implication of surface modification or texturing in boiling heat transfer enhancement 5

1.4 Motivation 5

1.5 Thesis structure 7

2. State of the Art 9-30

2.1 Historical background 9

2.2 Fabrication Methods (micro/nano textured surfaces) 12

2.2.1 Micromaching and Surface polishing 12

2.2.2.1 Physical coating methods 14

2.2.2.2. Spray coatings 14

2.2.2.3 Bonding with epoxy 15

2.2.3 Vapour deposition techniques 16

2.2.4 Chemical/Electrochemical methods 19-23

2.2.4.1 Electrochemical deposition (ECD) 21

2.2.4.2 Electrophoretic deposition (EPD) 23

2.2.5 MEMS/NEMS Technologies 23

2.3 Wettability effects on boiling heat transfer and bubble dynamics 25

2.4 Summary and research gap 26

2.5 Aim and objectives 29

3. Surface preparation and characterization 31-58

3.1 Coating method and materials 31

3.1.1 Pre-treatment and surface polishing 36

3.1.2 Hybrid nanofluid preparation 36

3.2 Surface characterization 40-46

3.2.1.1 TiO_2-SiO_2 coated surface 41

3.2.1.2 TiO_2-Al_2O_3 coated surface 44

3.2.1.3 SiO_2-Al_2O_3 coated surface 47

3.2.2 Energy Dispersive Spectroscopy (EDS) analysis 47

3.2.3 Coating thickness 49

3.2.4 Surface roughness 51

3.2.5. Contact angle measurements/wettability analysis 53

3.3. Summary 58

4. Experimental setup & procedure 59-72

4.1 Description of pool boiling apparatus 59

4.2 Experimental procedure 64

4.3 Calculation of Heat flux and other performance parameters 67

4.4 Uncertainty analysis 69

4.5 Validation of experimental setup 70

4.6 Summary 71

5. Pool boiling characteristics of water on textured surfaces 73-98

5.1 Pool boiling performance curve 73-79

5.1.1 Effect of TiO_2-SiO_2 coating 74

5.1.2 Effect of TiO_2-Al_2O_3 coating 75

5.1.3 Effect of SiO_2 - Al_2O_3 coatings 77

5.2 Effects on ONB temperature 79

5.3 Effects on heat transfer coefficient 82-92

5.3.1 Effect of TiO_2-SiO_2 coating 82

5.3.2 Effect of TiO_2-Al_2O_3 coating 86

5.3.3 Effect of SiO_2 - Al_2O_3 coatings 89

5.4 Wettability and roughness effects 93

5.5 Effects of coating thickness 95

5.6 Summary 97

6. Study of bubble visualization and dynamics 99-110

6.1 Description of visualization procedure 99

6.2 Bubble growth and visualization 100

6.3 Effect of surface roughness 102

6.4 Bubble dynamics 104

6.4.1 Bubble departure diameter 104

6.4.2 Bubble departure frequency 107

Summary 110

7. Conclusions and future work scope 111-116

7.1 Conclusions 112

7.2 Novelty of the thesis work 114

7.3 Keys benefits if apply this study in engineering applications 115

7.4 scope for future work 115

References 117-134

List of publications 135

………

LIST OF FIGURES

Fig. No.	Name	Page No.
Fig. 1.1	Typical pool boiling curve for saturated water at atmospheric pressure	3
Fig. 2.1	Categorization of micro/nano textured preparation methods and its associated techniques.	12
Fig. 3.1	Schematic illustration of electrophoretic deposition technique	32
Fig. 3.2	Sequence of various activities which was followed in the surface coating by EPD method.	37
Fig. 3.3	Photograph of bath sonicator (Model: GT-1730QTS, Frequency: 33/40 kHz, Power: 100 W).	37
Fig. 3.4	Photograph of Probe sonicator	38
Fig. 3.5	Illustration of two-step method for hybrid nanofluid preparation	38
Fig. 3.6	Zeta potential distribution of hybrid nanofluids	39
Fig. 3.7	FESEM image of polished (bare) Cu surface	42
Fig. 3.8	Surface morphology (FESEM image) of TiO_2-SiO_2 coated surface at two different magnification	43
Fig. 3.9	Surface morphology (FESEM image) of TiO_2-Al_2O_3 coated surface (CS2) at 20k, and 100k magnification	45
Fig. 3.10	Surface morphology (FESEM image) of SiO_2-Al_2O_3 coated surface (CS3) at two different magnification	46

Fig. 3.11 EDS spectrum of TiO_2-SiO_2 coated (CS1-5) surface. 48

Fig. 3.12 EDS spectrum of TiO_2-Al_2O_3 coated (CS2-5) surface 48

Fig. 3.13 EDS spectrum of SiO_2-Al_2O_3 coated (CS3-5) surface 48

Fig. 3.14 Measurement of coating thickness (cross section image FESEM) of TiO_2-SiO_2 coated surface 49

Fig. 3.15 Measurement of coating thickness (cross section image FESEM) of TiO_2-Al_2O_3 coated surface 50

Fig. 3.16 Measurement of coating thickness (cross section image FESEM) of SiO_2-Al_2O_3 coated surface 50

Fig. 3.17 Plot of coating thickness against the coating time 51

Fig. 3.18 Surface roughness profile of polished Cu (Bare) surface 52

Fig. 3.19 Surface roughness profile of coated surface 52

Fig. 3.20 Pictorial view of contact angle measurement facility 54

Fig. 3.21 Sessile drop image and contact angle measurement of a polished Cu (bare) surface 54

Fig. 3.22 Sessile drop image and contact angle measurement of TiO_2-SiO_2 coated surface 55

Fig. 3.23 Sessile drop image and contact angle measurement of TiO_2-Al_2O_3 coated surface 55

Fig. 3.24 Sessile drop image and contact angle measurement of SiO_2-Al_2O_3 coated surface 56

Fig. 4.1 Schematic diagram of pool boiling experimental setup 60

Fig. 4.2 Sample holder made of PTFE Teflon 61

Fig. 4.3 Schematic diagram of copper heating block with cartridge heater and sample holder arrangement 61

Fig. 4.4 Image of cartridge heater 62

Fig. 4.5 Image of K-type thermocouple 62

Fig. 4.6 Data acquisition system for temperature measurements 63

Fig. 4.7 Temperature distribution within copper heating block 63

Fig. 4.8 Pictorial view of an auxiliary heater 64

Fig. 4.9 Pool boiling test facility 65

Fig. 4.10 Plot of temperature profile at different heat flux which are measured by thermocouple in copper heating block 68

Fig. 4.11 Comparison of pool boiling data of bare surface with Rohsenow's model (1952) and experimental data 71

Fig. 5.1 Pool boiling performance curve of polished Cu and TiO_2-SiO_2 coated surface 74

Fig. 5.2 Pool boiling performance curve of polished Cu and TiO_2 - Al_2O_3 coated surface 76

Fig. 5.3 Pool boiling performance curve of SiO_2 - Al_2O_3 coated surfaces 78

Fig. 5.4 ONB points marked with the circle on the boiling curve of TiO_2-SiO_2 coated samples. 79

Fig. 5.5 Comparison of wall superheat temperature when bubble formation initiated on the surface 80

Fig. 5.6 Plot of heat transfer coefficient against the heat flux of TiO_2-SiO_2 coated and Polished Cu surfaces 83

Fig. 5.7	Variation in HTC enhancement at different heat flux onTiO_2-SiO_2 coated samples	84
Fig. 5.8	Plot of maximum enhancement in HTC and corresponding heat flux of TiO_2-SiO_2 coated samples	84
Fig. 5.9	Plot of experimental heat transfer coefficient against the heat flux of TiO_2-Al_2O_3 coated and Polished Cu surfaces	86
Fig. 5.10	Illustration of HTC enhancement on TiO_2-Al_2O_3 coated samples against the supplied heat fluxes	87
Fig. 5.11	Illustration of Max. Enhancement in HTC and corresponding heat flux on TiO_2-Al_2O_3 coated samples	88
Fig. 5.12	Variation of experimental heat transfer coefficient against the heat flux of SiO_2-Al_2O_3 coated and Polished Cu surfaces	89
Fig. 5.13	Variation in HTC enhancement at different heat flux on SiO_2-Al_2O_3 coated samples	90
Fig. 5.14	Plot of maximum enhancement in HTC and corresponding heat flux of SiO_2-Al_2O_3 coated samples	91
Fig. 5.15	Illustration of liquid-vapour interface	92
Fig. 5.16	Plot of free energy related function f(θ) against the contact angle (θ)	94
Fig. 6.1	Comparison of bubble generation (qualitative) on bare surface (hydrophilic) top row (a, b, c, & d), and composite surface CS2-5 (hydrophobic) bottom row (e, f, g, & h) at different heat flux.	101
Fig. 6.2	Illustration of bubble formation and departure phenomena on bare (hydrophilic) surfaces	101

Fig. 6.3	Illustration of bubble formation and departure phenomena on coated (hydrophobic) surface CS2-10	102
Fig. 6.4	Effects of roughness on bubble formation and their behaviour at three different heat flux condition	103
Fig. 6.5	Bubble departure diameter as function of Jacob Number (Ja) for TiO_2 -SiO_2 textured surfaces	105
Fig. 6.6	Bubble departure diameter as function of Jacob Number (Ja) for TiO_2 –Al_2O_3 textured surfaces	106
Fig. 6.7	Plot of bubble departure diameter against the Jacob Number (Ja) for SiO_2 –Al_2O_3 textured surfaces	106
Fig. 6.8	Variation of bubble departure frequency against the Jacob Number (Ja) on TiO_2 –SiO_2 textured surfaces	108
Fig. 6.9	Variation of bubble departure frequency on TiO_2 –Al_2O_3 textured surfaces	108
Fig. 6.10	Variation of bubble departure frequency at different Jacob Number (Ja) on SiO_2 –Al_2O_3 coated textured surfaces	109

LIST OF TABLES

Table. No.	Title	Page No.
Table 3.1	Potential advantages and disadvantages of EPD and other conventional technique	33-35
Table 3.2	Materials (nanoparticle) details	35
Table 3.3	Details of micro/nano composite coating parameters	41
Table 3.4	Arithmetic mean value of Surface roughness (Ra)	53
Table 3.5	Results of contact angle measurements on bare and coated surfaces	56
Table 4.1	Specifications of various Devices/Elements of experimental setup	66
Table 4.2	Uncertainty of measured parameters	69
Table 4.3	Estimated uncertainty of derived parameters	70
Table 5.1	Summarized result of optimum coating layer thickness and corresponding surface properties as well	96

LIST OF SYMBOLS

Nomenclature

h	Heat transfer coefficient (W/m^2 K)
h_c	Planck constant
h_{fg}	Latent heat of vaporization (J/kg)
k	Boltzmann constant
k_{cu}	Thermal conductivity of copper (W/m-K)
c_{pf}	Specific heat of fluid at liquid phase (J/kg-K)
D	Bubble diameter (m)
f_b	Bubble frequency (Hz)
$\boldsymbol{q''}$	Heat flux (kW/m^2)
T	Temperature (° C)
ΔT	(T_w - T_{sat}) Wall superheat temperature (K)
n_a	Active nucleation site density (sites/m^2)
T_1	Temperature of thermocouple location first (° C)
T_2	Temperature of thermocouple location second (°C)
T_3	Temperature of thermocouple location third (°C)
v	Volume (cm^3)
SiO_2	Silica dioxide
TiO_2	Titanium dioxide
Al_2O_3	Aluminum oxide
CS	Coated surface

Greek symbols

σ	Surface tension of liquid (N/m)
ρ_v	Vapor density(g/cm^3)
ρ_l	Liquid density (g/cm^3)
θ	Contact angle (˚)
Δ	Difference
$\emptyset$	Volume concentration

Subscripts

bf	Base fluid
np	Nanoparticle
d	Departure
f	fluid
w	wall
sat	saturation

Abbreviations

CHF	Critical heat flux
MaCE	Metal assisted chemical etching
LbL	Layer -by-layer
EPD	Electrophoretic deposition
ECD	Electrochemical deposition
CVD	Chemical vapour deposition
LPCVD	Low pressure chemical vapour deposition
PECVD	Plasma-enhanced chemical vapour deposition

MOCVD	Metal organic chemical vapour deposition
HFCVD	Hot filament chemical vapour deposition
ALD	Atomic layer deposition
DRIE	Deep reactive ion etching
BDA	Break down anodization
BIT	Boiling inception temperatures
PVD	Physical vapour deposition
GLAD	Glancing angle deposition
EBPVD	Electron beam physical vapour deposition
ONB	Onset of nucleate boiling
HTC	Heat transfer coefficient
BHTC	Boiling heat transfer coefficient
NBHT	Nucleate boiling heat transfer
DI	Deionised water
HF	Hydrofluoric
CCD	Charge-coupled device
CNT	Carbon nanotubes
ENM	Engineered nanomaterials
AFM	Atomic force microscopy
SEM	Scanning electron microscopy
FESEM	Field emission scanning electron microscopy
EDX	Energy dispersive X-ray spectroscopy
EDM	Electric discharge machining
NWs	Nanowires
RMS	Root mean square

CNTs	Carbon nanotubes
HFE	Hydrofluoroether
AAO	Anodised alumina oxide
PPA	Porous alumina
PTFE	Polytetrafluoroethylene
ITO	Indium tin oxide
SWCNT	Single-walled carbon nanotubes
MWCNT	Multi-walled carbon nanotubes
MEMS	Microelectromechanical systems
MPF	Micro-pin-fin