Experimental study on the influence of the downward facing surface characteristics on CHF

Bo Lin[1], Lei Zhang*[1], Junying Xu[1], Dongshan Wei[1], Hanzhe Liang[1], Xiangyu Yun[1], and Huiyong Zhang[1]

[1]: China Nuclear Power Technology Research Institute(CNPRI), CGN laboratory of COmprehensive Thermal-Hydraulic and Safety(COTHASE), Baolong fourth Road, Longgang District, Shenzhen, Guangdong, PR China

lin.bo@cgnpc.com.cn, zhangleicnpri@cgnpc.com.cn, xujunying@cgnpc.com.cn, weidongshan@cgnpc.com.cn, lianghanzhe@cgnpc.com.cn, yunxiangyu@cgnpc.com.cn, zhanghuiyong@cgnpc.com.cn

ABSTRACT

In-Vessel Retention (IVR) strategy is one of the most important severe accidents management strategies, which has been implemented in AP600, AP1000 et al. The key of IVR strategy is the heat flux on the RPV downward facing surface should lower than the Critical Heat Flux（CHF）of the corresponding location. However, with the increase of reactor power, the effectiveness of IVR strategy maybe decrease, which limited to the local Critical Heat Flux(CHF). Therefore, it is necessary to enhance the Reactor Pressure Vessel (RPV) downward facing surface CHF for the success of IVR strategy. In this paper, an electrical heating 316-stainless steel plate section is used to simulate the RPV downward surface situation for pool boiling and flow boiling experimental investigation at atmosphere pressure, which aimed to study the method to enhance the CHF of downward facing surface. Pool boiling experiments are designed to study the influence of surface roughness, surface manufacture technology and Al2O3 nanoparticle deposited on the CHF enhancement. While the flow boiling experiments were designed to study the influence of surface roughness on CHF at different orientation conditions. The results show that compared to smooth surface, roughness of the 316-stainless steel plate raise after sand-blasting, which enhance the CHF both on pool boiling and flow boiling experiment. On pool boiling experiment, CHF enhancements range from 13% to 21%, highest CHF 750kW/m^2 were get at Ra2.4μm surface , which is 21% higher than the smooth surface. On the study of surface manufacture technology on the CHF enhancement, find that sand-blasting gets higher increase than fiber-drawing technology, however, electroplating will decrease the CHF.Al2O3 particle deposited surface gets almost 30% enhancements than the plain surface. Through analysis, the Al2O3 particle deposited enhances the wettability of the surface, which results in the enhancements of CHF. On flow boiling experiment, finds that CHF increase at every orientation conditions, and the CHF is increase with the increase of surface roughness, but the highest increase is only 8.4% at Ra9.3μm surface.

KEYWORDS
IVR, CHF, surface roughness,CHF enhancement

1. INTRODUCTION

From the existing literature, nano fluid in boiling heat transfer is mainly on heat transfer surface to form a kind of nano porous surface structure, greatly change the wettability on the surface of the heat transfer, porous, roughness and vaporization core density, which related to the heat transfer parameters such as density, thus affecting CHF values. The porous structure of the surface is not sustainable, however, nanoparticles porous surface can be washed when the liquid flow rate is larger. The researchers hope that by surface processing method of enduring micro/nano structures on the surface of the heat transfer. Along with the development of micro/nano mechanical and electrical system technology(MEMS/NEMS),development and mature of surface micro/nano structure, various structures which beneficial to boiling heat transfer of convex(including micor/nano column, carbon nanotubes, etc), concave angle(micro/nano holes), porous surface(such as anodic oxidation, nano porous layer) are developed. The research shows that micro/nano structure mainly changes the wettability, surface roughness porosity, and all the several parameters to affect the boiling heat transfer.

Chih Kuang Yu et al[1] use the MEMS technology to machine micro hole on the surface of a silicon, using the FC-72 as a coolant, and conduct the pool boiling CHF under the normal pressure experiment. The experimental results show that CHF value can raise up to 300kW/m^2 after treatment of the surface, strengthening with the 2.5 times amplitude. The experiment also shows that the CHF density value is not will increase of pore desnity and infinite. Because of high density micropore can also lead bubbles to merger horizontally.

Kim et al.[2] use MEMS technology to process micron columns on the surface of silicon slice. They process 12 kind of surface with different micron size structures for pool boiling CHF experiment under normal pressure. The experimental results show that CHF increase by up to 350%, which is attributed to the increased capillary force. He also pointed out that there is a critical micron column spacing size, when the micron column spacing size is less than this critical size. CHF increases with the gap when the micron column gap is less than this critical size. CHF decreases with the increase of the gap when the gap is greater than this critical size.

Kim et al[3] produce four heat transfer surfaces. One of them is the coating surface with the diameter of micron, the other one is the nano-scale structure surface coated with ZnO, the third one is the composite structure surface containing both micro particles and ZnO nanoparticles, the fourth one is the untreated surface. The experimental result shows that the CHF value of the untreated surface is 1121kW/m^2, micro particle surface is 1652kW/m^2, nano coating surface is 2003 kW/m^2, composite structure surface is 2326 kW/m^2. The author points out that surface process enhances the surface wetting property of the heat transfer surface and liquid diffusion ability to increase the CHF.

Eric Forrest et al[4] process the surface using the nanoparticle layered assembly method , and prepare the superhydrophilic surface, hydrophilic surface and hydrophobic surface. CHF experiments are carried out at atmosphere pressure under pool boiling. The experimental results show that the CHF on superhydrophilic is the highest and the CHF on the hydrophobic is the lowest.

S.El-Genk[5] uses CNC technology to process the micro hole on the copper surface when conducting the pool boiling CHF experiments. The experimental results show that CHF is increasd by about 20%. Experiments also find that CHF of downward facing is 36% lower than that of upward facing. It is observed by high speed photography that most of the bubbles are generated at micropores, and the size and growth rate of bubbles increase with the increase of micropore diameter.

Renkun Chen et al[6] obtain the surface of Si nanowire structure and Cu nanowire structure respectively by using electroless erosion technology and electric feeding technology. The experimental results show that the nanowire structure improves the critical heat flux of the surface.

Thiagrajan et al.[7] melt copper particles with diameters from 5 to 20μm on the surface of copper blocks to prepare a porous dielectric coating heat transfer surface. using HFE-7100 as a coolant.

Pool boiling CHF experiment is carried out under normal pressure, and the experimental results show that CHF increased by 33% to 60%.
Hwang et al.[8] study the strengthening effect of surface porous coating on CHF, and carry out the CHF experiment under atmospheric pressure. The experimental results show that the presence of porous layer increases CHF by about 2 times.
Zhong et al.[9] take copper block as the heating section, process micro holes on the surface of copper block, use water as the coolant, and carry out CHF experiment of pool boiling under normal pressure to study the effect of micro hole density on CHF. The experimental results show that CHF value increases with the density of micropores. But the CHF enhancement is small.
After carrying out the influence of micropores on CHF, Zhong et al.[10] process the surface with fins again to study the influence of fins on CHF. The results show that the CHF value on the fin surface can be up to 3 times than that of the ordinary surface.
Y. Takata et al.[11] study the effect of TiO_2 coating on CHF by using water as a coolant to conduct pool boiling CHF experiment in copper tubes. The experimental section is exposed to ultraviolet radiation before heating. The results show that the contact angle of TiO_2 coating surface decreases with the increase of ultraviolet irradiation time. The CHF enhancement amplitude is up to 2 times.
Chin-chi Hsu et al.[12] used Si nano particles as coating to add on the surface of copper block, and use the hydrophobic agent trifluoromethane to change the humidity characteristics of the surface, and carry out the CHF experiment of pool boiling under normal pressure. The results show that the coating could change the solid-liquid contact angle on the heat exchange surface, and CHF decrease with the increase of contact angle.

Stutz et al.[13] conduct CHF pool boiling experiments with water as coolant, by addingγ-Fe_2O_3 nanoparticles on platinum heating wire, to study the effect ofγ-Fe_2O_3 nanoparticles of CHF. The results show that theγ-Fe_2O_3 nanoparticles coating rises up to a maximum of 90% CHF values, we find that nano coating on the surface of the contact Angle is smaller than untreated surface contact angle by measuring the contact angle. According to the analysis, the enhancement of surface moistening and stripping is an important reason for the improvement of CHF.
Mohammad et al.[14] use three particles of different sizes as coatings, namely Al_2O_3 (d<1μm. Nanometer scale),Al_2O_3(d<10μm, micron scale) and TiO_2(d<5μm), respectively, to conduct CHF up flow boiling experimental study in the pipe under normal pressure. The results show that the CHF increase of namo-scale $A1_2O_3$ coating is the largest (about 25%), followed by TiO_2 coating, while the increase of micro-scale Al_2O_3 coating was the smallest. According to the analysis, the antenna size of micron particle coating decreases, the wetting ability increases, and the core density of vaporization increases, resulting in the increase of CHF. The experimental results also show that CHF value increases with the increase of mass flow rate at the inlet, and increases with the decrease of inlet temperature.
Li lanlan has prepared smooth surface, micro groove surface, nano structure surface and micro nano composite structure surface, and carries out CHF experiment. The experimental results show that the critical heat flux of micro groove surface is 1.28 times higher than that of smooth surface. At the same time, it is found that porous nano-structures can significantly improve the wetting characteristics of the surface, and nano-structures can improve the heat transfer coefficient, while the heat transfer performance of micro-nano-composite structures is not as good as that of micro-groove surfaces.
Pang et al. research that the stick with glue method which adhesion nanostructures hydrophilic,

hydrophobic layer on the surface, the preparation of the three different according to the tentacles of the heat transfer surface. The experimental results show that the water meter jet CHF value on hydrophilic surface is higher than ordinary surface, and the water meter jet CHF value on hydrophobic surface is lower than ordinary the surface.

Klemen et al.[15] study the effect of surface roughness and surface processing technology on CHF. The experimental results show that when Ra is increased from 0.02μm to 15μm, CHF is significantly improved, and the CHF value of the surface processed with the same roughness Ra. It shows that a single roughness Ra cannot effectively measure the surface characteristics of CHF.

Hanley et al.[16] study the influence of roughness, hole wetness and porosity on CHF. The experimental results show that the surface roughness Ra could not change the impulse CHF. The improvement of surface wetting ability can strengthen CHF. The porous structure can be used to enhance CHF.

He et al. conduct the pool boiling experiments with changing the heating surface roughness by sandblasting, under the normal pressure. The study shows that compared with smooth surface, heating surface roughness increases after sandblasting, solid-liquid increase with the decrease of CHF values with tentacles.

Ahn[17], Jung[18] et al. study the effect of anodic oxidation on CHF. The experimental results show that the surface CHF is significantly increased with the increase of anodic oxidation time after the positive plate quantization. The analysis shows that with the increase of anodic oxidation time, the surface contact angle decreases, the liquid diffusion velocity increases, the vaporization core increases, and the effective heat transfer area increases, leading to increase CHF.

Song et al.[19] conduct the pool boiling experiment by using R-134a as a coolant. They study the effect on the CHF with 304 stainless copper winding wire. The experimental results show that most CHF increased by 114%. The mainly influence factor is the existence of the wire to separate the bubble is easy to do.

Bombardieri et al.[20] study the effect of the different heating surface material on CHF. The experiment selects copper, aluminum, stainless steel as heating surface material. It is suitable for hydrogen cooling system to conduct pool boiling for inspection. The experimental results show that CHF value on silk surface is 195kW/m^2, CHF value on aluminum surface is 115kW/m^2, and CHF value on stainless steel surface is 83kW/m^2.

To sum up, the CHF value can be effectively improved by surface treatment methods such as micro-nanopore, micro-nano column and surface particle deposition. Through the analysis of the wetability of the surface, it can be concluded that these surface treatment methods make the liquid-solid contact angle of heat transfer surface decrease and surface wetting ability increase, thus leading to the strengthening of CHF.

However, the research on the surface characteristics of CHF is still very inadequate. The mechanism of CHF enhancement by changing the surface characteristic did not find a valid conclusion by domestic and foreign scientific researcher. The current section of the surface characteristics of CHF research problems are mainly reflected in the following aspects.

1)the test section is mainly heating line and upward plate, when the RPV upper lower is downward facing heating plane. The inclination Angle is from 0 branches to 90, and the steam on the lower facing face is very different from that on the upper facing face.

2) the experiment conducts mostly in the pool boiling and the flow boiling experimental research is very little, while the actual cavity injection process under the severe accident, the cooling system is natural circle and close to the engineering characters.

3) in the outer surface of the actual RPV is aggravating, difficult to adopt MENS method, each is used to spray or shot peening technology, and both at home and abroad for sand blasting for during the CHF research is less.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1. Experimental Apparatus And Method

The test carried out in this paper was carried out on two kinds of test sites, namely flow boiling test device and pool boiling test device. Flow boiling test device was mainly used to study the CHF value of flow operation and the influence of azimuth angle on CHF, and pool test device was mainly used to study the strengthening measures for CHF.

Flow boiling device(figure.1.) is composed of test section, preheating section, mixer, circulating pump, water tank, flow meter, valve and temperature pressure system. Deionized water flow out as shown by the main pump, entering the preheater. The preheater heated the coolant to the target steam content after mixer filling outside mixing gas-liquid mixture into the test section space. The stainless steel plate in the test section was heated by DC power supply until CHF occurs. Finally, the high-temperature vapor-liquid compound separated from vapor-liquid through the heat exchange tank. The liquid coolant flowed into the generation loop for circulation, and the steam was discharged through the exhaust pipe.

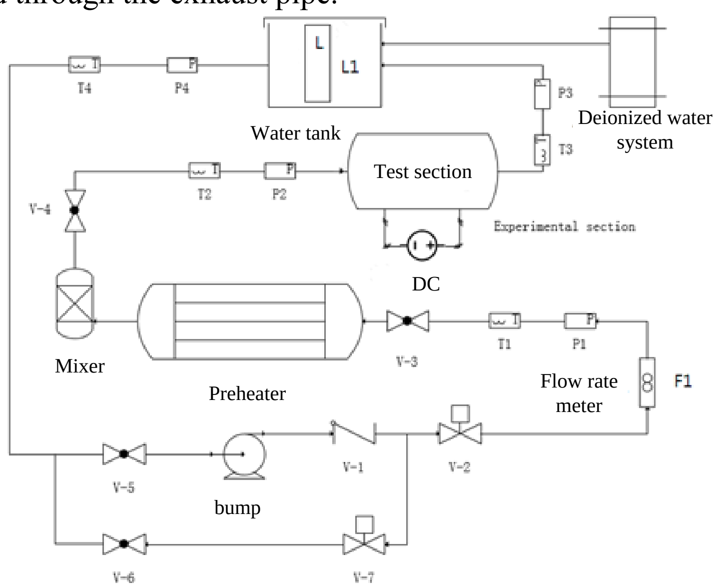

Figure 1. Schematic Diagram of the flow boiling experimental-loop

The pool boiling device(figure.2.) is composed of measurement and control system, DC power supply cabinet, water pool and test section. The water pool was the unique equipment of the pool boiling device, and other equipment was part of the flow boiling device. The test section was heated by the DC power supply to CHF. The voltage, current, temperature and other parameters on the test section were measured to calculate the CHF value. The water pool was compose of a stainless steel baseboard, two stainless steel side plate and two glass side plate which we can observe the boiling from it.

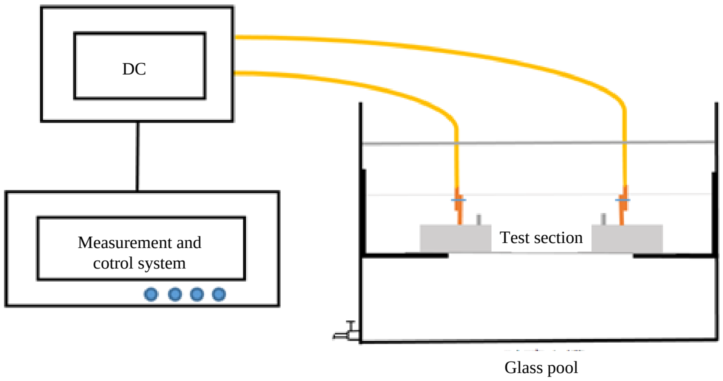

Figure 2. Schematic Diagram of the pool boiling experimental loop

2.1.1. Heating system of test section

The test section heating system(figure.3) consisted of DC power supply, copper platen, angle adjusting steel frame, test section state sealing device and stainless steel heating plate. The heating system in the experimental section had the heating function with protective measures in a certain control way. At the same time, with angle adjustment bracket, detachable test section seal blue device, replacement of heating steel plate and other ways to change the experimental conditions.

The DC power supply used in the heating system of the test section was SCR rectified very large power DC voltage stabilized temperature current power supply. The specification was 18V3000A. As the output current of the loop was large, copper strip with high conductivity and small resistance and knitted copper strip were used as the conductor to transfer the current. Knitted copper strip was connected with stainless steel heating plate through copper electrode to form a closed conductive circuit, and the heating section steel plate was electrically heated. During the test, the DC power supply supported setting the overpressure protection function, and the protection value can be customized.

The heating steel plate was made of 316 stainless steel, the size was 200mm×50mm×1mm. The machining error was ±1mm, ±1mm, ±0.1mm. All the heating steel plate was made of the same processing material and method. According to the test requirements, 5 thermocouples could be arranged on the surface of the heating steel plate to detect the temperature change of the points in the surrounding area. The heating steel plate was connected with welded shoulder copper electrode, and the fixed L-type copper electrode was connected with rotten copper electrode through copper bolts to form a closed electrification loop. In order to ensure the insulation between the power circuit and the frame body, high-temperature sealant was filled between the steel plate and the seal cover, as shown in the figure.

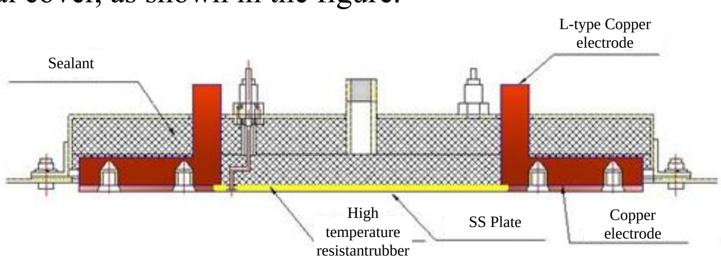

Figure 3. Schematic Diagram of test section

The test section was fixed on the angle adjusting bracket, and the knitting comparison pipe is connected to the platform body to form a circulation loop. The level of angle adjusting bracket is 0-90°. Adjustable angle adjusted according to different test conditions.

2.1.2 Preheating section heating system

The preheating heating system was composed of distribution cabinet, preheater and mixer. The function of the preheating system was to control the heating power for the loop coolant, and then the heating coolant fully flowed through the mixer to be a liquid-vapor compound, and finally to the test section heating area. The roof thermal period of rated voltage was 380V. The heating power transformed from 0-160 kW. The test section position by controlling the input power machine produced matching steam conditions of coolant, outside test RRV generation face different working conditions of the upstream area of target azimuth.

2.1.3 Bit-control and measurement system

This test belonged to the high temperature heating test, the test should not be approached for a long time when testing, at the same time demand to monitor the parameters and environment. So we built the instrument system to control the operating system, obtaining parameters and the on-site feedback. The experimental programmed system included the direct current power system, the preheating section system, electric valve opening control system. DC power supply could be controlled by the software routine. The preheating power regulation, the main loop and the opening control electric circuit could be controlled on WinCC control for remote operation.
This test needed to measure the parameters including coolant temperature, flow rate, loop pressure, the direct current, voltage and the heating steel plate surface temperature. The temperature and pressure were measured before and after test section, before the preheater and after water tank.

2.1.4 Deionized water supply system

The coolants used in the general test adopt the deionized water. The deionized water used in laboratory could be divided into three levels: level 1 water, require electrical resistivity should higher than 10MΩ·cm(conductance below 0.1μs/cm), mainly used for analysis experiment which have strict requirements, level 2 water, require electrical resistivity should higher than 1MΩ·cm(conductance below 1μs/cm), mainly used for inorganic measurement analysis experiment, level 3 water, require electrical resistivity should higher than 0.27MΩ·cm(conductance below 1μs/cm), mainly used for general chemical analysis experiment. The coolant used in this test adopt the water which electrical resistivity higher than 10MΩ·cm.

2.2 Experimental Method

2.2.1 Test plane surface processing mode

The test changed the surface roughness by pneumatic sand blast. This test used brown corundum sand to do the pneumatic sandblasting. The different roughness were processed by changing the number of sands and sandblasting time. Corresponding to the roughness, the mesh number and sandblasting pressure presented as the table.1.

Tables, such as Table I, are numbered in Roman numerals, with the table title in **boldface** centered above the table with a blank line between the title and actual table. Use two blank lines before and after the table.

Table I. surface process by sandblasting

Roughness Ra(μm)	Mesh number	Sandblasting pressure(MPa)
1.6	180	0.4
2.4	120	0.4
3.2	80	0.4
4.3	60	0.5
6.3	40	0.5
9.3	16	0.5

In addition to sandblasting, in order to study the influence of surface processing technology on CHF, the test also treated the surface of the test plane by drawing process and electroplating process. After drawing, the roughness Ra of the stainless steel surface was 1.6μm, and after electroplating, the test clean plate surface would form a layer of clear and thin copper coating. In this test, Marr roughness meter was used to detect the roughness precision of the processed plate of non-show steel, and the processing effect of the surface of the plate was in line with the expectation after the test.

2.2.2. nano coated surface

The Al_2O_3 nanometer coating surface was prepared by boiling heating. To nanoparticles coating was prepared, the test first, the preparation of water-based $A1_2O_3$ nano fluid, and then puts the test plane of nano fluids, by DC power to electrical heating test of stainless steel plane, the water-based $A1_2O_3$ nano fluid heated to boiling state. In the hours after boiling nanoparticles in nano fluids was deposited in the stainless steel test plane cleaned surface.

2.2.3. CHF criterions

The DC power increased with the increase of current, DC power supply when the current is added, voltage can be calculated by the current multiplied with loop resistance. Loop resistance included wire resistance and experimental plate resistance, which occupied the main part of whole loop resistance. From the physical properties of the 316 stainless steel, the resistance of the 316 stainless steel increased with the temperature rises. In the heating process when the DC power supply was energized for the heating section, the output voltage of the loop was fed back by the real-time measurement of the DC power supply. Before CHF occurs, with the increase of power, the temperature of the test plane slowly increased, and the resistance value and voltage of the test plane slowly change. When CHF occurs, the plane surface heat transfer form changed from nucleate boiling state to film boling state, at this point, the heat transfer surface bubbles populations and together as a covering of heating area, and then plane surface heat transfer coefficient decreased quickly, the test plane surface heat transfer rapidly deteriorating, the test plane could be not insufficient cooled, at the same time due to the stainless steel resistance increased with the temperature increasing, the feedback voltage of DC power supply was also rapidly increased. Therefore, the CHF could be determined by measuring the degree of temperatur of the stainless steel plane and the voltage reverse decoration value of the DC power supply. CHF could be determined when the temperature of the stainless steel plane increased at a rapid speed and the DC power supply voltage rises to a significant convergence.

2.2.4.CHF calculation method

The test plane was heated by the DC power supply. The power of the test plane could be calculated if the voltage and current was known. The heat from the test plane to the coolant could be the result of the total power minus the other side heat. The input power of test plane can be obtained:

$$Q_T = I \times U \tag{1}$$

The Qu power of the stainless steel heated backward is obtained by Fourier guiding law.

$$Q_u = \lambda_i \times \frac{\left(\bar{t}_i - \bar{t}\right)}{\delta_i} \times L \times W \tag{2}$$

Heat transfer power of stainless steel side was,

$$Q_s = \lambda_s \times \frac{\left(t_{i1} - t_3 + t_{i5} - t_2\right)}{\delta_i} \times \left(W \times H\right) - 2q \times \left(L \times H\right) \tag{3}$$

By arranging the above formula, it can be known that the heat flux of the coolant

$$q = \frac{UI - \lambda_{\mathrm{i}} \dfrac{(\bar{t}_i - \bar{t})}{\delta_{\mathrm{i}}}(L \times W) - \lambda_{\mathrm{s}} \dfrac{(t_{i1} - t_3 + t_{i5} - t_2)}{\delta_{\mathrm{s}}}(W \times H)}{1.04(L \times W)} \tag{4}$$

In the above formula, λ_{i} and λ_{s} respectively denoted the heat conduction coefficient of thermal insulation material and 316 stainless steel(i.e. heated plane material), they are 1.2W/(m·℃) and 16.3W/(m·℃) respectively. $\bar{t}_i$ and $\bar{t}$ denoted the average temperature of the plane upper surface and test inlet and outlet. δ_{i} and δ_{s} denoted the thickness of heat insulation material and the distance between temperature and copper, respectively. The value of them are 0.003mm and 0.001mm. t_{i1}, t_{i5}, t_2 and t_3 denoted the temperature of the location near oulet of test on the plane , the location near inlet of test on the plane, test inlet and test outlet, respectively. L, W, H denoted the length, width and thickness of the test plane. The value are 0.2m, 0.05m, and 0.001m, respectively.

2.3 Test Conditions

This paper mainly studied the influence of the surface characteristics on CHF. Since the CHF formation mechanism of pool boiling and flow boiling was different, the surface characteristics of the two boiling forms need to be studied respectively. In this paper, the effect of sandblasting and nano-coating on CHF was studied. Therefore, the test conditions can be divided into four types, summarized in Table.II.

1. The surface of the test thin plate was sandblasted with standard jade sand with different mesh numbers to form the test plate with different surface roughness. The influence of surface roughness on the CHF toward the downward facing wall in pool boiling was studied.

2. The surface treatment of the test plate was carried out by means of wire drawing and electroplating technology and the influence of surface processing technology on the CHF value toward the downward facing wall in pool boiling was studied.
3. Prepare the aluminum oxide nanoparticle coating test plate, and studied the influence of aluminum oxide nanoparticle creep layer along the particles on the CHF value toward the downward facing wall in pool boiling.
4. Sandblasted the surface of the test plate with different number of brown corundum sand, forming different roughness surfaces.
All the pool boiling tests are performed at the 0 angle.

Table II. surface process by sandblasting

Experimental type	The influence factor	Experimental condition
Pool boiling	Roughness	The effect of roughness on CHF downward facing wall
Pool boiling	Surface process	The effect of surface process on CHF downward facing wall
Pool boiling	Nano-coating	The effect of nano-coating on CHF downward facing wall
Flow boiling	roughness	The effect of roughness on CHF downward facing wall
Pool boiling	Roughness	The effect of roughness on CHF downward facing wall
Pool boiling	Surface process	The effect of surface process on CHF downward facing wall

3. EXPERIMENTAL RESULTS

3.1 Influence of Surface Roughness under Pool Boiling

The test plates used in this kind of test were the plates which were processed by pneumatic sandblasting. Ra were selected to be 0.8µm, 1.6µm, 2.4µm, 3.2µm ,4.3µm ,6.3µm and 9.3µm. The experimental results were shown in figure 4. It could be seen from the graph, compared with the smooth plate, the sandblasting plate increased, the CHF of the degree of phase Ra for 2.4µm is highest, reached 750 kW/m^2. But removing the CHF of 2.4µm, the other CHF values were similar, all about 720kW/m^2. It could be concluded from the analysis of the actual test results that, compared with the smooth plate, CHF of the plate after surface phase-change is worth improving, but CHF value does not increase with roughness, but there is a polar point. The point happened near 2.4µm.

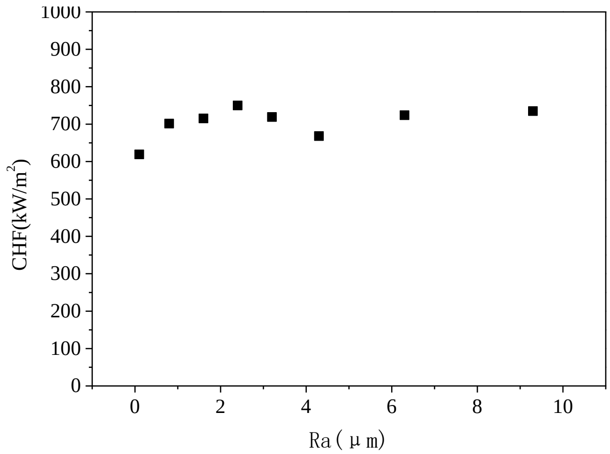

Figure.4 CHF related with the Ra

3.2 Influence of Surface Process under Pool Boiling

To study the influence of surface process on CHF, four test plates were used to conduct CHF experiments under pool boiling. One was 1.61μm Ra plate which was processed by drawing, the second one was 1.61μm Ra plate which was processed by sandblasted, the third one was the plate processed by electroplate, the fourth was the smooth plate. The test results were shown in figure 5. It can be seen from the diagram, for the same Ra l.6μm, the CHF of sandblasting surface treatment and drawing surface treatment was different. The CHF with sandblasting surface was 715.26kW/m^2, while the CHE with drawing surface is 635kW/m^2. The CHF value of the surface sandblasting treatment is higher than that of the CHF of the drawing surface. Both of them were higher than that of the smooth plate. The CHF with electroplate surface was 415kW/m^2, 30% lower than the smooth plate.

From the analysis of test results, it can be concluded that (1) the rough surface would affect CHF, compared with smooth plate, CHF was strengthened after roughness increasing; (2) the processing technology had an effect on CHF in the downward surface under the condition of pool boiling. For the local rough process, the strengthening effect of sandblasting technology on CHE was greater than that of the drawing process.(3) sand blasting and drawing process are used to produce the same roughness Ra, but the CHF obtained was different, indicating that CHF was affected by other factors, such as processing technology.

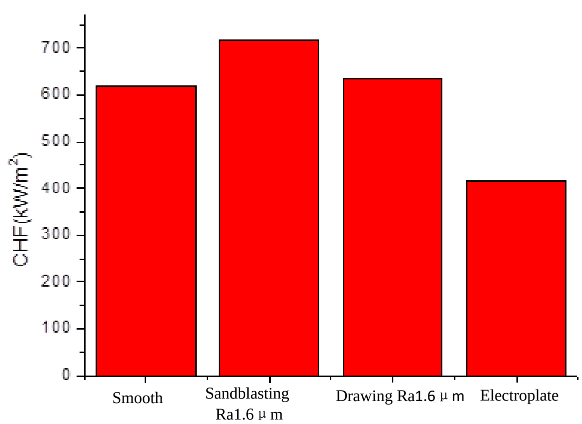

Figure.5. The influence of surface process on CHF

3.3 Effect of Oxidized E Nano-Coating on CHF under Pool Boiling

From the research status at home and abroad in previous part, it could be concluded that the strengthening factor on CHF was the nano coating formed at the heating plate during boiling.
In this paper, the water-based Al_2O_3 nano fluid with 0.4% volume concentration was used when the smooth plate was heated in it. The nano particles can deposited on the heating plate to form the nano coating plate. The CHF with nano fluid was 791.8kW/m^2, increased 30% than the that with deionized water. The CHF with the nano coating palte was 789.76kW/m^2. The results were shown in figure.6.

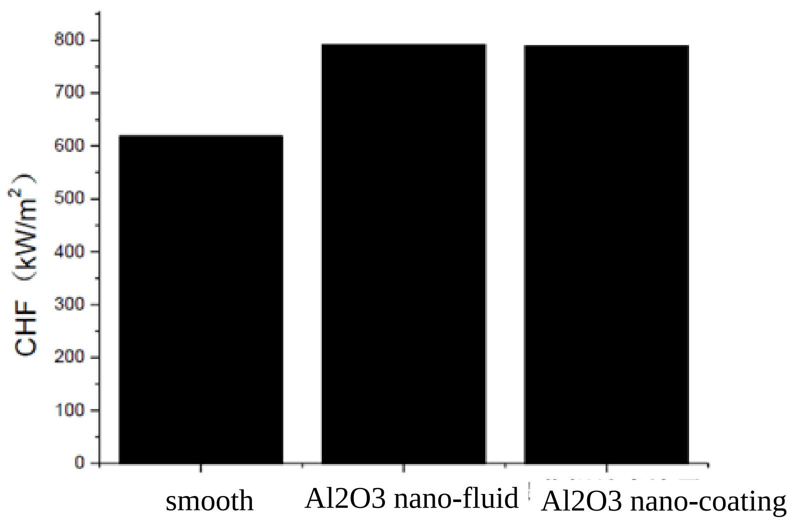

Figure.6. The influence of nano-coating on CHF

3.4 Influence of Roughness Surface under Flow Boiling

The flow boiling test design needed the same degrees, the same pre heating power and the same flow rate. Five difference roughness plate processed by sandblasting were used in the flow boiling test.in this test, the angle was 46°, power of preheating section was 31kW and liquid volume of main loop was 11.3m^3/h. the velocity of the water flow rate at the inlet was 0.23m/s. the roughness of the surface were 2.4μm, 3.2μm, 4.3μm, 6.3μm and 9.3μm.
The results were shown in figure.7. It could be seen that the CHF with smooth plate was 1033.17kW/m^2. The CHF improved to a certain extent after sandblasting, and the degree of improvement is greatly changed in a linear relationship with the surface phase flexibility, wherein, the CHF value with a surface phase Ra of 9.3μm reached 1120.35kW/m^2. In general, the CHF enhancement effect was not very obvious. For the heating section with a surface phase accuracy Ra of 9.3μm, the CHF enhancement effect was only 8.4%.

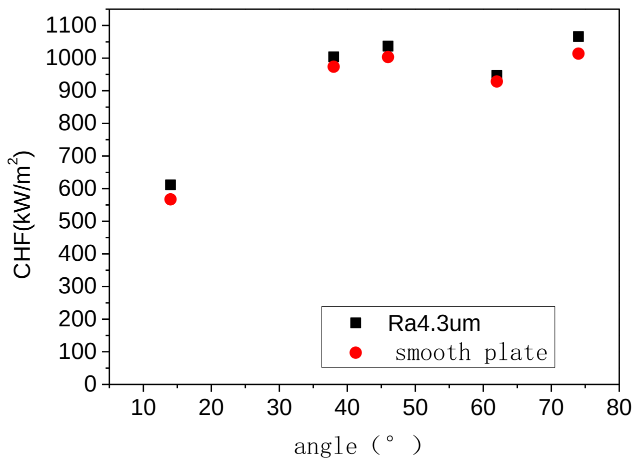

Figure.7 the influence of roughness on CHF in flow boiling

3.5 Summary

In this chapter, the influence of surface roughness, surface processing technology and the Al_2O_3 coating on CHF was analyzed in pool boiling test. The influence of surface roughness on CHF in flow boiling test was analyzed. The results showed that the CHF enhancement after the surface roughed under pool boiling or flow boiling. The influence of the surface processing technology for CHF study found that the CHF using sandblasting process was higher than that using drawing process, which showed that CHF also affected by other parameters. In the study on the influence of the nano coating, it was found that the Al_2O_3 nano coating could significantly strengthen CHF.

4. INFLUENCE OF SURFACE MICROSTRUCTURE ON CHF

Existing studies have shown that surface microstructure would have an impact on CHF. This quantity would analyze the actual test results from the two perspectives of surface fluidity and surface microstructure. The real inspection blessed by using scanning electron microscopy measurements made form on the surface of a stainless steel heating, scanning electron microscopy (SEM) was between the transmission of electroplating and optic microscope between a good view of malicious wait means, can be directly used to material performance of the sample surface microstructure into, including electron optical system, electronic system, display unit and the vacuum system. SEM released electron beam through the electron gun, and electron beam under the action of accelerating voltage converged the electronic probe through electromagnetic optic lens. Under the effect of scan coil, especially on the sample surface scan bed type, such as secondary electron, scattering electronic, x-ray et al. After this information detected, the photoelectric conversion and signal amplification processing further, the line on the display shows the characteristics of the sample.
In this experiment, Czech TESCAN MIRA3 scanning electronic microscope was used. The amplification could be up to 1 million times, with the minimum resolution of 1nm and the maximum size of 12-inch sample. Figure 8 showed the microstructure of different surfaces.
It could be seen from the figure, the surface of the smooth plate is very flat. By comparing the smooth plate and the plate after sandblasting, it can be found that there are some irregular pits on the surface of the tested thin plate after sandblasting, and the pit size increased with the size of

roughness. In the study, it was also pointed out that CHF would change with the change of spacing between micrometers, and there was a critical distance. When the actual moment between micrometers was less than this critical value, CHF increased, and when the actual distance between micrometers was greater than this critical value, CHF decreased. Combined with the domestic and foreign research status and the results of the test, CHF increased with roughness could be analyzed: (1) the contact area between the plate and coolant increased with increasing of roughness, that is, the effective area of heat transfer increased, however the area for calculating the CHF still is calculated according to the original area, leading to CHF calculated value is higher than plate of CHF. (2) the degree of surface roughness add, surface pit size increases, leading to increased capillary force, droplet valley easy infiltration in the pit, to delay the occurrence of CHF. (3) bubble escape frequency changed after the surface coarse degree changed, thus affecting CHF values. But the bubble escape frequency was not always increased with roughness, there is a critical value, when the surface roughness is equal to the critical value, the bubble escape frequency was highest, the CHF value was biggest.
By comparing the electroplate plate and the smooth plate, it could be found that the surface of the electroplate in the actual test becomes more smooth than the smooth plate, which leaded to the poor adsorption ability of the droplet on the surface, and thus leaded to the decrease of CHF.
However, the nano-coating surface of the junction was distributed with regular nanoparticles, and the size was 1μm to 2μm. The presence of nanoparticles would also lead to the increase of heat transfer area, with the increase of vaporization core and delay the occurrence of CHF.

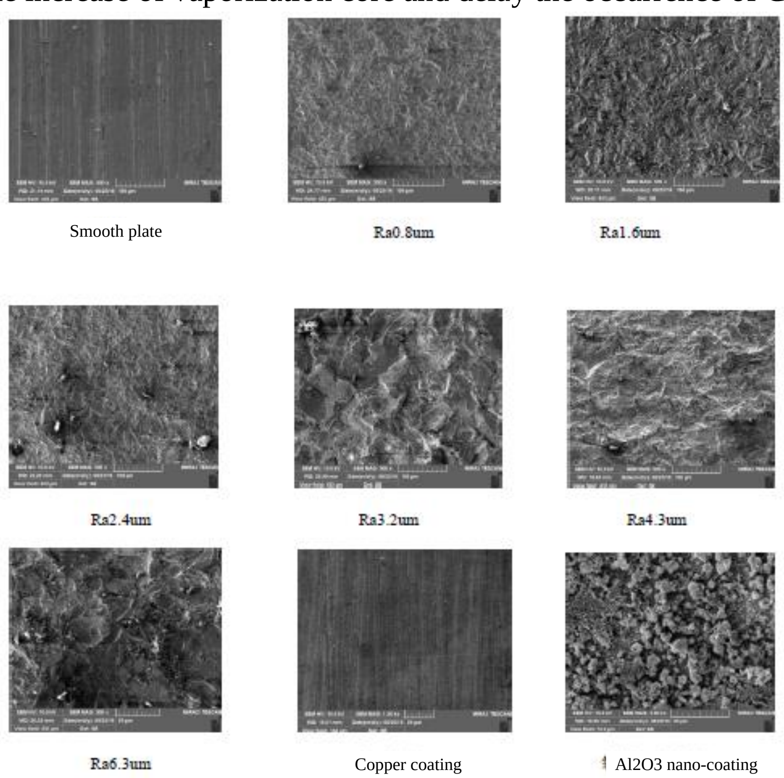

Figure.8 microstructure with different surface

In this chapter, the surface contact angle and surface microstructure was analyzed with the result of the experiment. From the analysis, it could be obtained the following conclusions: (1) heat transfer surface wettability would affect CHF, the enhancement of surface wettability could help improving CHF values. (2) the surface would have concave after sandblasting, and pit size could increase with the increasing roughness. The existence of the pit would affect evaporation core, bubble escape frequency, bubble escape diameter, which changed CHF. (3) the effective heat transfer area of the heat transfer surface after roughness and nano-particle coating would increase, resulting the larger CHF calculated.

5. CONCLUSION

316 stainless steel plate heaters are used to conduct the pool boiling and flow boiling tests for CHF on the downward facing wall surface at atmospheric pressure. In pool boiling test, the influence of the roughness, surface process, Al_2O_3 nano-coating is researched, and the mechanism discussed. In the flow boiling test, the influence of roughness is analyzed.
The following conclusions are drawn from the experiment: 1) CHF have a great enhancement in the pool boiling when CHF have little improvement in the flow boiling after roughness. the CHFs are similar in pool boiling test when the CHF increase with roughness in flow boiling test. 2) CHF is affected with other parameter, except for roughness, such as the surface process.3) the presence of nanoparticle obviously enhances the CHF 4) the wettability of surface can increase the CHF. 5) From the results of the microstructure on the surface, the mechanism of CHF enhancement is that the surface microstructure change after surface process. The microstructure will affect the parameters such as the vaporization core, bubble escape frequency, bubble escape diameter, which changes CHF.

REFERENCES

1. Yu C K, Lu D C, Cheng T C. Pool Boiling Heat Transfer on Artificial Micro-Cavity Surfaces in Dielectric Fluid Fc-72[J]. Journal of Micromechanics & Microengineering, 16(10):2092-2099(2006).
2. Kim S H, Lee G C, Kang J Y, Et Al. Boiling Heat Transfer and Critical Heat Flux Evaluation of The Pool Boiling on Micro Structured Surface[J]. International Journal of Heat & Mass Transfer, 91:1140-1147(2015).
3. Kim S, Kim H D, Kim H, Et Al. Effects Of Nano-Fluid and Surfaces With Nano Structure on the Increase of CHF[J]. Experimental Thermal & Fluid Science, 34(4):487-495(2010).
4. Forrest E, Williamson E, Buongiorno J, Et Al. Augmentation of Nucleate Boiling Heat Transfer and Critical Heat Flux Using Nanoparticle Thin-Film Coatings[J]. International Journal of heat & Mass Transfer, 53(1-3):58-67(2010).
5. El-Genk M S, Suszko A. Effects of Inclination Angle and Liquid Subcooling on Nucleate Boiling on Dimpled Copper Surfaces[J]. International Journal of Heat And Mass Transfer, 95: 650-661(2016).
6. Chen R, Lu M C, Srinivasan V, Et Al. Nanowires for Enhanced Boiling Heat Transfer[J]. Nano Letters, 9 (2): 548-553(2009).
7. Thiagarajan S J, Yang R, King C, Et Al. Bubble Dynamics and Nucleate Pool Boiling Heat Transfer on Microporous Copper Surfaces[J]. International Journal of Heat & Mass Transfer, 89:1297-1315(2015).
8. Hwang G S, Kaviany M. Critical Heat Flux In Thin, Uniform Particle Coatings[J]. International Journal of Heat & Mass Transfer, 49(5–6):844-849(2006).
9. Zhong D, Meng J, Li Z, Et Al. Experimental Study of Saturated Pool Boiling From Downward Facing Surfaces with Artificial Cavities[J]. Experimental Thermal & Fluid Science, 68:442-451(2015).
10. Zhong D, Meng J, Li Z, Et Al. Critical Heat Flux for Downward-Facing Saturated Pool Boiling on Pin Fin Surfaces[J]. International Journal of Heat & Mass Transfer, 87:201-211(2015).
11. Y. Takata, S. Hidaka, M. Masuda, T. Ito, Pool Boiling on A Superhydrophilic Surface, Int. J. Energy Res. 27: 111–119 (2003).
12. Hsu C C, Chen P H. Surface Wettability Effects on Critical Heat Flux of Boilingheat Transfer Using Nanoparticle Coatings[J]. International Journal of Heat and Mass Transfer, 55(13): 3713-3719(2012).

13. Stutz B, Morceli C H S, Da Silva M F, Et Al. Influence of Nanoparticle Surface Coating on Pool Boiling[J]. Experimental Thermal and Fluid Science, 35(7): 1239-1249(2011).
14. Mohammad Sohail Sarwar *, Yong Hoon Jeong, Soon Heung Chang. Subcooled Flow Boiling CHF Enhancement with Porous Surface Coatings[J] International Journal of Heat & Mass Transfer. 50:3649-3657(2007).
15. Ferjančič, Klemen, And I. Golobič. "Surface Effects on Pool Boiling CHF."Experimental Thermal & Fluid Science25.25:565-571(2002).
16. O'hanley H, Coyle C, Buongiorno J, Et Al. Separate Effects of Surface Roughness, Wettability, and Porosity on The Boiling Critical Heat Flux[J]. Applied Physics Letters, 103(2):024102 -024102-5(2013).
17. Ahn H S, Chan L, Kim H, Et Al. Pool Boiling CHF Enhancement by Micro/Nanoscale Modification of Zircaloy-4 Surface[J]. Nuclear Engineering & Design, 240(10):3350-3360(2010).
18. Jung J Y, Kim H, Kim M H. Effect of Ionic Additive on Pool Boiling Critical Heat Flux of Titania/Water Nanofluids[J]. Heat & Mass Transfer, 49(1):1-10(2012).
19. Song S L, Chang S H. An Experimental Study on CHF Enhancement of Wire Nets Covered Surface in R-134a Flow Boiling under High Pressure and High Mass Flux.
20. Bombardieri C, Manfletti C. Influence of Wall Material on Nucleate Pool Boiling of Liquid Nitrogen[J]. International Journal of Heat & Mass Transfer, 94:1-8(2014).