creative commons
COMMONS DEED

저작자표시-비영리-변경금지 2.0 대한민국

이용자는 아래의 조건을 따르는 경우에 한하여 자유롭게

- 이 저작물을 복제, 배포, 전송, 전시, 공연 및 방송할 수 있습니다.

다음과 같은 조건을 따라야 합니다:

저작자표시. 귀하는 원저작자를 표시하여야 합니다.

비영리. 귀하는 이 저작물을 영리 목적으로 이용할 수 없습니다.

변경금지. 귀하는 이 저작물을 개작, 변형 또는 가공할 수 없습니다.

- 귀하는, 이 저작물의 재이용이나 배포의 경우, 이 저작물에 적용된 이용허락조건을 명확하게 나타내어야 합니다.
- 저작권자로부터 별도의 허가를 받으면 이러한 조건들은 적용되지 않습니다.

저작권법에 따른 이용자의 권리는 위의 내용에 의하여 영향을 받지 않습니다.

이것은 이용허락규약(Legal Code)을 이해하기 쉽게 요약한 것입니다.

Disclaimer

dCollection

[UCI]I804:48009-200000501606

Thesis for the Degree of Master of Science

Experiments and simulation study on a droplet falling down to the hydrophobic/hydrophilic surface

The Graduate School

University of Ulsan

Department of Naval Architecture and Ocean Engineering

WANG QUN

Experiments and simulation study on a droplet falling down to the hydrophobic/hydrophilic surface

AssociateProfessor Rho-Taek Jung

A thesis

submitted to
the Graduate School of the University of Ulsan
In partial fulfillment of the requirements
for the Degree of Master
By

WANG QUN

Department of Naval Architecture and Ocean Engineering
Ulsan, Korea

July 2021

Experiments and simulation study on a droplet falling down to the hydrophobic/hydrophilic surface

This certifies that the thesis of Wang Qun is approved

____

Committee Chair: Professor Yoon-Rak Choi

____

Committee Member: Professor Hyung-Taek Ahn

____

Committee Member: Associate Professor Rho-Taek Jung

Department of Naval Architecture and Ocean Engineering

Ulsan. Korea

July 2021

Acknowledgements

First of all, I would like to express my heartfelt thanks to my Professor Rho-Taek Jung! From the topic selection of the paper, the collection of documents, the design of the framework, the layout of the structure, to the final draft of the paper, from the content to the format, from the title to the punctuation, Without Professor Rho-Taek Jung hard cultivation and diligent teachings, I would not have completed the paper smoothly. In the process of the experiment, the Professor gave careful guidance and help, and in the writing of the paper, the Professor also made serious modifications. Therefore, this paper has not only borne my efforts and sweat, but also devoted a lot of efforts and energy of the Professor.

Secondly, I would like to thank to professor Yoon-Rak Choi and Professor Hyung-Taek Ahn for their helpful advices and comments for my thesis.

I would like to thank the two students in the laboratory for their communication, which has benefited me a lot.

In the laboratory life and study, Professor Jung has been strict with me, to my scientific research and life careful guidance, I benefited a lot. Every time I was worried about the progress of the experiment, Professor Jung carefully enlighten me, pointing out the maze, so that I through one experiment. With the help of Professor Jung, my scientific research level has been greatly improved. At the same time, Professor Jung's rigorous attitude towards teaching and scientific research and his approachable style of doing things have left a deep impression on me, which will be a precious treasure in my life.

Finally, I would like to thank my family. Their hard work and selfless support have given me the courage to face difficulties and accept challenges.

Abstract

Droplet impact on hydrophilic and hydrophobic wall is a common phenomenon in the field of life and industry. When the droplets impact the wall, it forms a contact angle θ with the wall. When $\theta>150^\circ$, the surface is super-hydrophobic; $150^\circ>\theta>90^\circ$, the surface is hydrophobic; $30^\circ<\theta<90^\circ$, the surface is hydrophilic; and $\theta<30^\circ$ is super-hydrophilic. This paper focuses on the impact force between droplets and hydrophilic and super-hydrophilic surface, and the morphology comparison between droplets on hydrophilic and super-hydrophilic surface. Falling on the horizontal fixed wall can be divided into four stages: movement stage, expansion stage, contraction stage and equilibrium stage. The influences of droplet diameter, velocity and contact angle on droplet diffusion width, rebound height and wall impact force were compared numerically. A high-speed camera and a PCB sensor were used to capture and measure the interface and impact force of the droplet in the collision with the different wall surface, and the simulation results were compared with those of fluent. In fluent simulation, based on the VOF model, simulated the impact forces of droplets impact different contact angles and different walls. The results show impact force is related to the droplet diameter and impact velocity and the contact angle has little effect on the impact force. Change the bottom boundary and the impact force is greater without the slip boundary, According to the experimental results, when there is a liquid film on the wall, the impact force decreases with the thickness of the liquid film. Finally, the comparison between experiment and simulation shows that the slip boundary is more suitable for comparison with experiment.

Keywords: Hydrophobic surface, Hydrophilic surface, VOF, Experiment, Impact force

List of Figures

Figure1.1 Spreading(left)splash(middle) and bouncing(right) of droplets 2

Figure1.2 Contact angle 4

Figure1.3 Expected bubble shapes for different Reynolds and Weber numbers 5

Figure1.4 Surface characterization and dynamic behavior of water droplet impact on super-hydrophobic surfaces at different Froude number. 6

Figure2.1 Experiment setup 11

Figure2.2 Diagram of sensor assembly 13

Figure3.1 Computational domain 14

Figure3.2 Model build 17

Figure4.1 Droplet falling at a height of 10cm hitting a hydrophobic solid wall 21

Figure4.2 Droplet falling at a height of 10cm hitting a hydrophilic surface 23

Figure4.3 The height of the droplet varies with time 24

Figure4.4 The width of the droplet varies with time 24

Figure4.5 Droplet falling down to the bottom plate(shown left upper to right down) 25

Figure4.6 The falling process of a droplet 26

Figure4.7 Spreading width with time 27

Figure4.8 The droplet height varies with time 28

Figure4.9 Super-hydrophilic spray 29

Figure4.10 Impact force of hydrophilic surface 30

Figure4.11 Impact force of super-hydrophilic surface 30

Figure4.12 The process of droplet spreading on two wall surfaces(When the droplet 32

Figure4.13 Jet flow phenomenon 33

Figure4.14 Liquid film initial state 33

Figure4.15 The spread of a droplet on impact 33

Figure4.16 The impact force of a droplet on a film of water 34

Figure4.17 The impact force of a droplet on a drop 34

Figure4.18 The process of droplet spreading on two surfaces 35

Figure4.19 Comparison of impact forces in different conditions 35

Figure4.20 Computational domain 36

Figure4.21 Peak impact force of different meshes 37

Figure4.22 Comparison of the simulated and experimental results of the impact force of water droplets 38

Figure4.23 Simulation of droplet impact force 38

Figure4.24 Impact force at different contact angle with time 39

Figure4.25 Impact force at different droplet diameter with time 40

Figure4.26 Impact force at different velocity with time 41

Figure4.27 Simulation comparison of the two boundaries 42

Figure4.28 Experimental and simulated comparison of impact forces 43

Contents

Acknowledgements		i
Abstract		ii
List of Figures		iv
Contents		vi
1	**Introduction**	**1**
	1.1 Research status	2
	1.2 Dynamic behavior of droplet impacting wall surface	2
	1.3 Spread width	3
	1.4 Contact angle	4
	1.5 Weber number	5
	1.6 Froude number	5
	1.7 Numerical Simulation	6
2	**Experimental method**	**10**
	2.1 Experimental setup	10
3	**Simulation with the Navier-Stokes Equation(FLUENT)**	**14**
	3.1 Navier-Stokes Equation	14
	3.2 DesignModeler introduction	17
	3.3 Tecplot introduction	18
	3.4 Contact angle and boundary conditions	18
	3.5 Solver selection	18
	3.6 Calculate region initialization	19
	3.7 Impact force report definition	19
	3.8 Calculate stability and convergence	20
4	**Results**	21
	4.1 Droplets impact the hydrophobic surface	21
	4.2 Droplets impact the hydrophilic surface	22
	4.3 Simulation results with the Navier-Stokes Equation	25

4.4 Comparison of experimental and simulation 25
4.5 Width comparison between simulation and experiment 27
4.6 Height comparison between simulation and experiment 28
4.7 Impact force of droplet impact dry wall condition(Experiment) 28
4.8 Impact force of droplet impact on liquid film 32
4.9 Numerical calculation method of droplet impact force 36
4.10 Verification of mesh 37
4.11 Influence of contact angle on impact force 39
4.12 Influence of droplet diameter on impact force 40
4.13 Influence of velocity on impact force 41
4.14 Influence of different boundary on impact force 42
4.15 Experimental and numerical comparison of impact forces 43
6 conclusion 44
Reference paper 45

Chapter 1

Introduction

Marine organisms have a great impact on the pollution of the ship, if the use of self-cleaning paint can effectively prevent biological attachment, reduce the ship resistance. It is common to form hydrophobic and super-hydrophobic surfaces for self-cleaning. The effect of objects and solid walls directly affects the actual effect of industrial process. This paper mainly studies the process of droplets impacting hydrophobic and hydrophilic walls. The falling behavior of droplets has been studied for more than 100 years. Between 1805[1] and 1867[2], a great deal of research has been done on the behavior of droplets impacting solid walls.

Since then, a large number of research reports have been reported, most of which are theoretical combined methods to study the interaction between liquid droplets and solid wall surface. It can be found that [3],the morphology of droplets after impact on the solid wall has a great relationship with the initial state of droplets and the physical parameters of the wall. These parameters include droplet density, diameter, surface tension, impact velocity, impact angle, viscosity and wet-ability, roughness and temperature of the wall surface. [4]Also found that in addition to the above factors, the surrounding gas pressure also has an influence on the droplet's falling behavior. In general, when the Weber number is low (the impact velocity is small), the phenomenon of partial or complete rebound will occur after the droplets impact the super-hydrophobic surface [6]. The phenomenon of rebound is generally due to the good hydrophobic of the solid surface and the small adhesion of the wall surface during the rebound process of the droplet. Droplets detach easily from solid surfaces. If it is a hydrophilic solid surface, the droplet cannot rebound in time during the retracting process and will form a spreading state [5]. At high Weber number, coronal sputtering will occur after droplets impact the wall surface [6].

1.1 Research Status

Since Worthington[7] first studied the special phenomena caused by droplet impact on the wall and liquid pool in 1908, researchers at home and abroad have conducted a large number of studies on the morphological changes of droplet impact wall for more than a hundred years. The existing literatures mainly focus on theoretical analysis, numerical simulation and experimental research. In this paper, the dynamic characteristics and influencing factors of droplet impact on solid wall are studied.

1.2 Dynamic behavior of droplet impacting wall surface

When a droplet hits a solid wall, it will spread, retract, deposit, splash, bounce and other dynamic behaviors according to the physical properties of the droplet and the state of the wall. When the droplet has high wet-ability and low impact velocity, it will spread completely and the liquid film almost does not shrink after hitting the wall, that is, it will spread and deposit completely after hitting the wall. When the impact velocity is high or the roughness of the wall surface is irregular, the droplet will produce rapid sputtering phenomenon after impact on the wall surface, that is, compared with the complete liquid film in the spreading process, the liquid film is broken or even splashed. One kind of crown-like sputtering is called "crown sputtering". When the super-hydrophobic surface and the temperature of the wall are high, the droplet will partially or completely bounce off the wall after hitting the wall

Fig1.1 Spreading (left) splash (middle) and bouncing (right) of droplets

1.3 Spread width

In 1967, the factors affecting the droplet maximum spreading diameter were studied. They concluded that the inertial and viscous forces controlled the droplet spreading and deformation processes, while the properties of the solid wall had little effect on the droplet initial spreading process, and mainly affected the droplet retracting process and the time required for the droplet to reach equilibrium state. due to the complexity of the droplet impact process, the theoretical derivation of the maximum spreading diameter is mainly considered from two aspects: one is to establish the energy equation of the droplet initial and spreading to the maximum diameter state respectively, and to derive the maximum spreading diameter that the droplet can reach after impact from the perspective of energy conservation. Among them, it is very difficult to accurately define the viscous dissipated energy in the process of motion, which leads to some differences among different models of maximum spread diameter. Collings[8] assumed that the final spreading state was disk-shaped, ignored the viscous dissipation, and deduced the maximum diameter spreading coefficient based on energy conservation as follows:

$$\beta_{\max} = ((We+12)/(1-\cos\theta)^{1/2} \tag{1.1}$$

In order to consider the influence of viscous dissipation, Avedisian[9]used the following formula to solve the maximum spreading coefficient:

$$\beta_{\max} = [1/3(We+4)/(1-\cos\theta)^{1/2} \tag{1.2}$$

PasandidehFard[10]improved the previous formula for solving the spreading coefficient, and believed that most of the viscous dissipation was generated in the boundary layer, and improved the volume expression in the calculation process to obtain the common formula for the spreading coefficient as follows:

$$\beta_{\max} = ((We+12)/[3(1-\cos\theta)+4(We/\sqrt{\mathrm{Re}})]]^{1/2} \tag{1.3}$$

During the experiment, Ukiwe [11] found that there were obvious errors between the model of maximum spreading straight diameter in existing literatures and the experimental results. Formula was used to calculate the viscous dissipation, and the final result was that the deviation between the maximum spreading diameter and the experimental results was less than 5%

$$W = (\pi/12)\eta D_0^2(\beta_{\max}/1.2941)^5 \tag{1.4}$$

In addition to the perspective of energy conservation, the other approach is to analyze the impact process from the perspective of fluid dynamics. By establishing the mass conservation equation and N-S equation, considering the influence factors such as contact angle and capillary force in the dynamic process, the maximum spreading diameter is solved theoretically. Due to the difficulty of theoretical solution, many assumptions and simplifications are often required. Nevertheless, the results of theoretical derivation can provide a reasonable explanation for the dynamic behavior changes of droplet impingement process. No matter which way, because of the complexity of droplet dynamic process, it is always difficult to solve the droplet dynamic process accurately.

1.4 Contact angle

Contact angle refers to the angle between the solid-liquid interface through the liquid interior and the gas-liquid interface at the three-phase junction of solid, liquid and gas. The contact angle of liquid on the surface of solid material is an important parameter to measure the wet-ability of liquid on the surface of material. By measuring the contact angle, we can get a lot of information about the solid-liquid and solid-gas interface interaction on the material surface.

If θ<150°, the solid surface is super-hydrophilic, that is, the liquid is not wetting the solid surface, If 90°<θ<150°, then the solid surface is hydrophobic, f 30°<θ<90°, then the solid surface is hydrophilic. If θ<30°, surface is super-hydrophilic, the liquid is easier to wet the surface, and the smaller the angle, the better the wet-ability.

There are usually two methods for measuring contact angle: one is shape image analysis method; the latter is often called a wetting balance. But the most widely used, the most direct and accurate measurement or shape image analysis method.

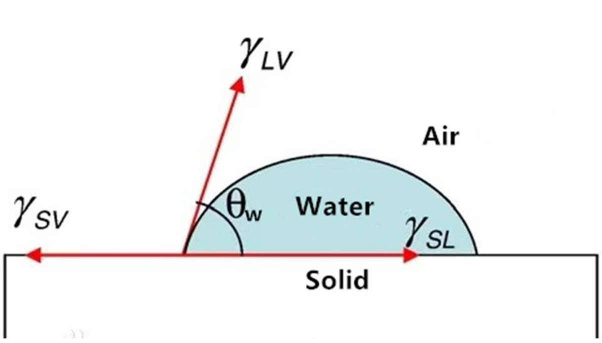


Fig1.2 Contact angle

1.5 Weber number

$$W_e = \frac{\rho \upsilon^2 l}{\sigma}$$

Where ρ is the fluid density (Kg/m3), *v* is the characteristic velocity (m/s), *l* is the characteristic length (m), σ is the surface tension coefficient of the fluid (N/m).The Weber number represents the ratio of the inertial force to the surface tension effect, and the smaller the Weber number, the more important the surface tension, such as capillary phenomena, soap bubbles, surface tension waves and other small-scale problems. In general, for large scale problems, where the Weber number is much larger than 1.0, the effect of surface tension can be ignored.

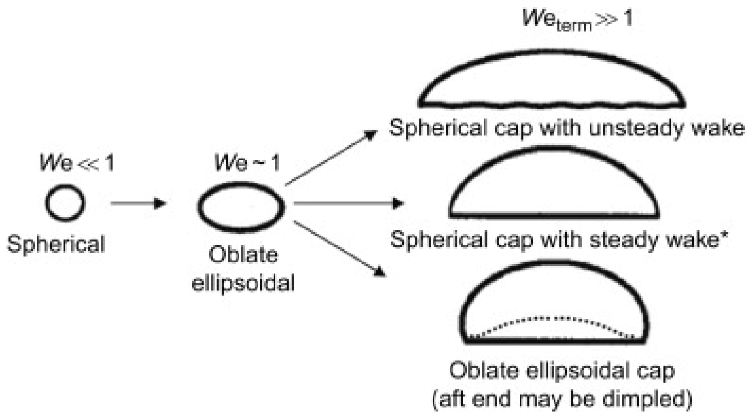


Fig1.3 Expected bubble shapesfor different Reynolds and Weber numbers

1.6 Froude number

$$Fr = \frac{\upsilon}{\sqrt{gl}}$$

Ratio of inertial force to gravity in the fluid: To judge the flow pattern of open channel by using Froude number:

When Fr<1, the water flow is slow; Fr=1, water flow is critical flow; Fr>1, the current is a rapids.

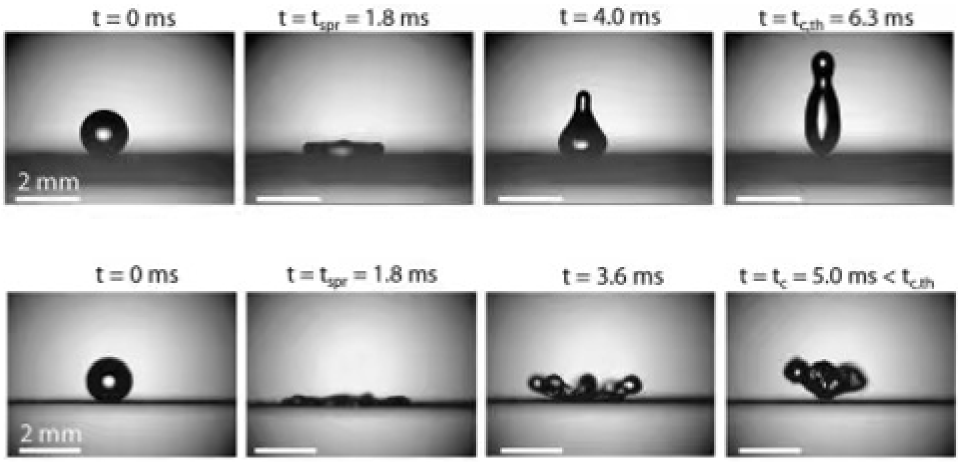


Fig1.4 Surface characterization and dynamic behavior of water droplet impact onsuper-hydrophobic surfaces at different Froude number.

1.7 Numerical Simulation

Numerical simulation is a new research method in recent years. The process of droplet impinging on the wall is a gas-liquid two-phase flow problem, and the key to the problem is to accurately calculate the gas-liquid interface in the process of movement. Among the existing simulation methods, the extraction of phase interfaces can be mainly divided into two categories: one is interface capture based on Euler method, and the other is interface tracking based on Lagrange method [12, 13].Among them, the typical methods are ALE (arbitray-lagrange-eulerian), Eulerian and Allagrange mixed method, MAC method. At present, the typical representative method of Euler's method is widely used: The fluid volume method (VOF) [14, 15], the level set method [12], and the LS growth VOF method combining the advantages of the fluid volume method and the level set method [16]. In addition, there is the mesoscopic scale based lattice LB method [17].Numerical model of droplet size, impact velocity, liquid itself physical properties, viscosity, surface tension (table), the surface contact angle, surface wet-ability, the impact angle of incidence on the droplet spreading after bumping, maximum spreading diameter, retraction form, dynamic behavior such as crushing and rebound is simulated, and the droplet impact wall ever dynamic process simulation results can be identical with the experiment, Liang Chao et al. [14,18] simulated the impact of liquid droplets on walls with different wet-ability, and found that the droplets spread out after impact, liquid film fracture, and partial and complete rebound. Simulation results show that the droplets collision speed, the maximum spread out straight diameter increases, as the liquid viscosity increases, in the process of droplet spreading and retraction can increase consumption, obvious inhibiting effect to the droplet dynamic behavior [15], viscosity and surface tension of the droplet splash after bumping influence on behavior, and the liquid surface tension and viscosity more hours, The more likely it is to splash after impact. Longli et al. [17] adopted lattice LB model to simulate the dynamic behavior of two droplets impacting on liquid film, and found that the smaller the viscosity, the smaller the internal interaction of droplets, and the more prone to splash behavior after droplets impacting on rough wall, and the more prone to rebound phenomenon on hydrophobic and super-hydrophobic wall surfaces. In the treatment of wall wet-ability, the model usually selects a static contact angle as the boundary condition, which has a large deviation from the actual dynamic contact angle changed in the process of droplet impact, resulting in errors between the simulation results and the experimental results. Bussman [19] extracted the forward contact angle and the backward contact angle from the experimental photos, and fused them into the model to simulate the dynamic behavior of droplets after collision on the inclined wall and 45°stepped wall, thus reducing the error between the model and the experimental data. Wang and Chen [20] used the dissipative ion dynamics method to simulate the influence of different wet-ability pillar surface structures on droplet motion, and found that the non-uniform wet-ability had a significant influence on the dynamic contact angle of droplet. When the droplet slides in the non-uniform area, its forward angle and backward angle both increased. Chen Yuanyuan [21] simulated the "droplet microarray" by placing hydrophilic points regularly on the wall surface and using VOF method to simulate the special dynamic behavior of droplet impact on the non-uniformly wet-able wall surface compared with that on the uniformly wet-able wall surface, which has a special guiding significance for cell screening or lithographic printing and other behaviors. The model can well calculate the pressure field and velocity field inside the droplet, which is helpful to explain the dynamic behavior after impact. Li found that the maximum compressive stress after impact appeared on both sides of the droplet center in the spreading process [22], which was somewhat different from the simulation results of Liang Chao et al. [18] that the maximum pressure appeared at the droplet center near the wall. Li Jiayu [23] believed that the phase field method was more advantageous to calculate the surface tension in the description of the phase interface because it considered the interface stress effect. The phase field method was adopted to solve the singularity near the contact line and the dynamic contact angle model of Yokoi [24] was combined to study the dynamic wetting process of droplets. Although most of the models can well simulate the dynamic behaviors such as spreading, shrinking, bouncing and sputtering after the droplets impact on the wall and thin liquid film, the mechanism of sputtering and bouncing behaviors remains to be studied. The boundary conditions of the dynamic contact line in the model are still not agreed, and the effects of wet-ability and roughness on the dynamic evolution of droplets still need to be further studied. This paper mainly studies the droplets impacting solid surface, but the process of the droplet striking is very complex, only rely on the experiment observation is not enough, so on the basis of experiment, combined with numerical simulation and theoretical analysis to explore the droplets rebound behavior and vibration frequency and impact force and the relationship between the solid surface and droplet.

The investigation shows that there are many researches on the spreading and bounce-back of droplet wall surface. However, there is almost no research on the impact force of droplet impacting on different wall surfaces. Therefore, experimental method and numerical simulation method are used in this paper to simulate and analyze the impact force of droplet

CFD simulation and experimental method were used to study the expansion and retraction of water droplets after collision with a smooth wall. Based on VOF (volume flow) method, the simulation results are in good agreement with the experimental data.CFD is a combination of modern fluid mechanics, numerical mathematics and computer science. It is a frontier science with strong vitality. It uses various discrete mathematical methods to carry out numerical experiments, computer simulation and analysis on various problems of convective mechanics, so as to solve various practical problems.

Compared with traditional CFD software, Fluent has the following advantages:

1. Good stability. A large number of numerical examples show that the results calculated by FLUENT are in good agreement with the experimental results.

2. Rich models. Fluent includes a variety of computational models, such as multiphase flow model, heat transfer and combustion model, etc. These models can be applied to almost all fluid-related fields.

3. Accuracy is improved. Due to the adoption of multi-grid accelerated convergence technology and a variety of solution method, FLUENT has better solution accuracy.

4. FLUENT provides the functions of the secondary development interface so that users can solve their own specific problems conveniently.

This paper is divided into four chapters, the second chapter, we introduced the experimental set up, the third chapter N-S method, the fourth chapter is analyses the results and comparison, and chapter five summarizes the paper.

Chapter 2

Experiments

2.1 Experimental setup

The experimental system of droplets impinging on hydrophobic and hydrophilic and super-hydrophilic walls is shown in the figure. The cover film of mobile phone used in the experiment is hydrophobic wall surface, and its static contact angle is 100° by measuring from a graphical analytical tool after taking a photo snapshot. The hydrophilic material is ordinary glass with a static contact angle of 55°. During the experiment in Fig.2.1, when the syringe was slowly pushed, the droplet was in a quasi-static state under the balance action of gravity and surface tension. Therefore, the droplet volume at the time of dripping only depended on the outer diameter of the injection needle, which ensured that droplet can be produced under different experimental conditions. The impact process of the droplet was recorded by a high-speed camera. In order to better record the behavior of droplets impacting on two types of solid surfaces, the hydrophobic and hydrophilic experiment was filmed at a rate of 320×240 and 16,682 fps with a frame rate of 59.94 micro-second. During the shooting, a front light source is set, the droplet impact point and the high-speed camera are arranged in the same horizontal straight line, and the front image of the deformation process of the droplet impact on the wall is recorded. In the experiment, a ruler was placed in the same scene depth of the droplet impact point to ensure the accuracy of later data processing. Each experiment was repeated for several times, and the measurement error was controlled within 5%.

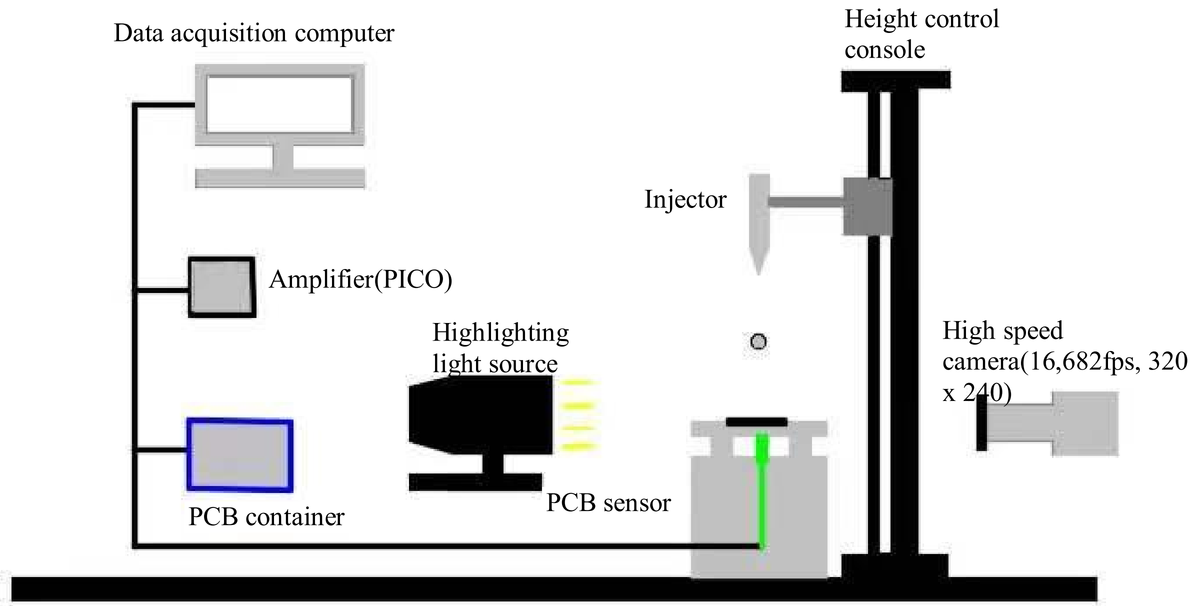


Fig2.1Experiment setup

The apparatus for the experiment of droplet impinging on solid surface includes an iron platform with adjustable height, a syringe, a needle head, a xenon lamp, a light, a high-speed camera, and an acrylic plate. The impact velocity of droplet was controlled by adjusting the height of the injector needle. In the experiment, a high-speed camera was used to capture the course of droplet collision with the wall surface, and image processing software was used to collect and analyze the data of the captured images. Droplet with a radius of 1.2mm and initial height of 10cm were used to calculate the experimental and numerical values, and the variation of spread number and rebound height with time was analyzed. Two samples of hydrophilic glass and mobile phone toughened film with hydrophobic were selected for comparative test. By slowly pushing the syringe, the fluid produced droplets at the needle, which fell off under the action of gravity and hit the wall surface. A high-speed camera was used to capture the impact process of the droplets. The velocity and size of the impinging droplet were analyzed by the image software. When the water drops impact the glass sample, they will adhere to the solid surface, and on the toughened film surface, it can be observed that the droplets bounce off the surface, and after several impact tests, the sample surface is still dry. Therefore, the cover film has good hydrophobic, and its adhesion to the liquid drops is less than that of glass. The droplet impact process involves energy conversion. In the initial impact stage, the droplet has certain kinetic energy and surface energy. In the spreading stage, the kinetic energy of the droplet is transformed into surface energy and dissipated energy. In the shrinkage stage, the surface energy is converted into kinetic energy and dissipated energy in the shrinkage process. If the surface has a small adhesion force, the energy consumed in the droplet retraction process will be reduced, and more surface energy can be converted into the kinetic energy of the droplet and escape from the surface. On the surface of the cover film with less adhesion, the impingement droplets bounce continuously. When the droplets impact the different surface with different velocity and diameter, it will produce different dynamic behaviors. In the droplet shape experiment, the wall surface is hydrophilic, super-hydrophilic and hydrophobic, and the super-hydrophilic wall is made by super-hydrophilic spray.

To measure the impact force, the distilled water in the syringe is first pushed through a hose towards the mouth needle. Under the action of gravity, water drops off the needle. The droplet diameter is 4.64mm, and the impact velocity is 2.8m/s. The surface diameter of the sensor is 5mm.The impact force between the water droplets and the wall surface is transmitted to the sensor through the bottom of the impact plate (PCB Model111A26).The sensor converts the impact force into an electrical charge signal. The charge signal is converted into voltage signal by charge amplifier (PICO) and transmitted to the computer for storage and processing. There are usually two methods for determining droplet impact velocity: free falling body calculation and high speed photogrammetric instrument. for low velocity liquid drops, the difference between the impact velocity calculated by using the free-falling body square method and the velocity obtained by high velocity photogrammetric instrument is only 3.In this paper, the free-falling body square method is used to calculate the initial impact velocity when the liquid drops collide with the wall surface, $v = g\sqrt{\frac{2h}{g}}$, Where, h is the distance from the top of the needle to the wall surface of the collision plate; g is gravity velocity.

PCB (Model111A26)	
Sensitivity	1.45 mV/kPa

Fig 2.2Diagram of sensor assembly

Chapter 3

Simulation with the Navier-Stokes Equation(FLUENT)

3.1 Navier-Stokes Equation

Fig. 3.1 shows the calculation region division of the cube grid, which is used to simulate the process of a droplet impacting a plane. The length, width and height of the cube are W=15mm (x) × 10mm (y) × 15mm (z), respectively, and the whole computing space can meet the needs of droplet diffusion. In order to select the appropriate minimum cell, different mesh sizes were tried. In order to meet the calculation requirements and ensure the calculation accuracy, the mesh size is divided into 0.01mm

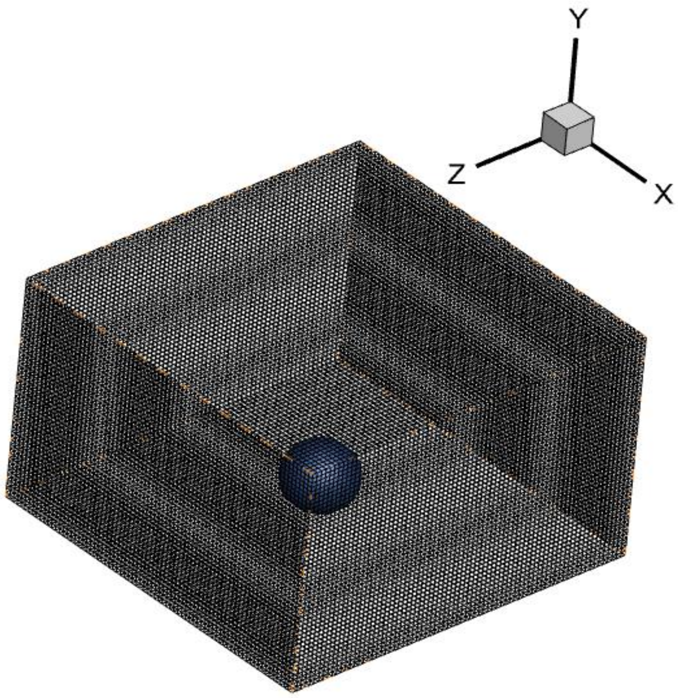


Fig3.1Computational domain

In this paper, FLUENT software Design Modeler is used to build the geometric model and divide the mesh. The modeling in this chapter is mainly to observe the change of droplet shape and the change of droplet impact force on the plane under the conditions of different velocities and different contact angles. In numerical simulation, in addition to controlling equations and setting reasonable boundary conditions, appropriate initial conditions are also needed. The selection of reasonable initial conditions is very important to the accuracy of calculation results. In this paper, the initial distribution of the fluid in each phase is set as follows: the air phase is defined as the main stage with an initial volume integral of 0, and the water density is defined as the second stage with a volume fraction of 1. In this way, the whole calculation area is filled with air, the volume fraction is 0.Using the Adapt Region function in Fluent, the spherical position area occupied by the initial droplet was marked 1mm from the bottom of the wall surface. Finally, through Patch function, the volume fraction of this region is set as 1, that is, the second phase water. The shape of the initial droplet can be observed through the contour phase diagram.

In the VOF model, the phase fluids must not be interpenetrated with each other. Its simulation is achieved by solving a set of Navier-Stokes equations and the volume fraction of one or more secondary fluids tracked throughout the domain. The volume fraction (s) of the second phase is obtained by solving the phase continuity equation

$$\frac{\partial}{\partial t}(\alpha_s)+\nabla\cdot(\alpha_s\vec{v}_s)=0 \tag{3.1}$$

The volume fraction of the initial phase cannot be solved by this equation, but the volume fraction of the initial phase can be solved by equation

$$\alpha_p+\sum\alpha_s=1 \tag{3.2}$$

The momentum equation is the application of Newton's second law in fluid mechanics, that is, the increment of the fluid momentum in the control body in unit time is equal to the sum of the external forces acting on it in unit time. In the VOF method, a single momentum equation in the whole region is solved, and the resulting velocity field is shared by all phases. As shown below.

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla\cdot[\mu(\nabla\vec{v}+\nabla\vec{v}^T)]+\rho\vec{g}+\vec{F} \tag{3.3}$$

Where, P is static pressure, ρ and μ represents volume average density and dynamic viscosity respectively:

$$\rho=\alpha_s\rho_s+(1-\alpha_s)\rho_p \tag{3.4}$$

$$\mu=\alpha_s\mu_s+(1-\alpha_s)\mu_p \tag{3.5}$$

The subscripts p and s in equation (3.4) and (3.5) represent the initial phase and the second phase respectively.

In this paper, there are only two phases of water and air in the simulation. The expression equation of the volume force $\vec{F}$in Equation (3.3) in the continuous surface tension model (CSF) is as follows

$$\vec{F}=\sigma\frac{\rho k_s\nabla\alpha_s}{\frac{1}{2}(\rho_p+\rho_s)} \tag{3.6}$$

In Equation (3.6), $\sigma$is the surface tension coefficient between the initial phase and the second phase, and$k_s$is the surface curvature of the second phase, calculated from the surface local gradient perpendicular to the phase interface. In the literature of the continuous surface force (CSF) model proposed by Brackbill et al, the calculation equation of kis as follows:

$$k=-(\nabla\hat{n}) \tag{3.7}$$

In Equation (3.7),$\hat{n}$is the unit normal vector, $\hat{n}$and the force is calculated through the volume fraction gradient of the second phase, as shown below:

$$\hat{n}=\frac{\nabla\alpha_s}{|\nabla\alpha_s|} \tag{3.8}$$

When the continuous surface tension model is used in the VOF model, the contact angle of the wall should be given to adjust the normal direction of the element surface near the wall rather than to strengthen the boundary conditions of the wall itself. The surface curvature of the phase interface near the wall can be adjusted by setting the wall contact angle. The surface normal vector of the actual unit near the wall is expressed as:

$$\hat{n}=\hat{n}_w\cos(\theta_w)+\hat{t}_w\sin(\theta_w) \tag{3.9}$$

Among them,$\hat{n}_w$and $\hat{t}_w$are the unit normal vector and tangent vector of the wall surface, and θ_w are the contact angle of the wall surface. Together with the direction of the surface normal vector obtained from the normal calculation of the unit, the local curvature of the surface is determined, and the curvature is used to adjust the volume force term of the surface tension calculation

The basic steps of solving by FLUENT are as follows:

1. Establish the geometric model and divide the grid

2. Enter and check the grid

3. Identify the model

4. Determine fluid physical parameters

5. Determine boundary conditions

6. Determine droplet area

7. Determine control parameters

8. Solve initialization

9. Iterative calculation

3.2 Design Modeler introduction

Design Modeler is a common CFD preprocessing software tool with very complete geometric modeling capabilities. The basic elements of a grid are node, edge, surface, and body. It can create points, lines, planes and bodies in a variety of ways, supporting Boolean operations between geometries.

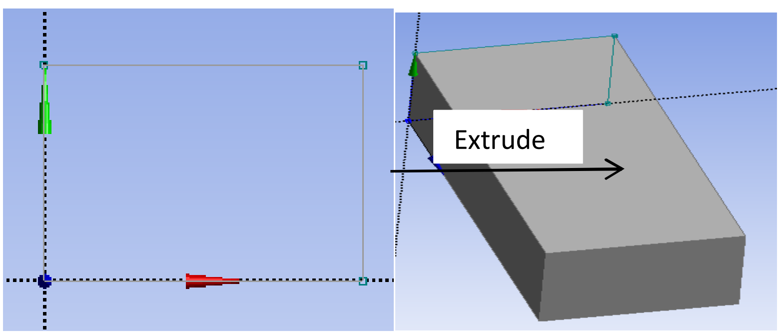


Fig 3.2 Model build

3.3 Tecplot introduction

Tecplot software is powerful visual processing software for plotting. Deal simple X-Y curve graph, 2D and 3D surface drawing of various formats to 3D volume drawing formats. It has FLUENT software special data interface, can directly read *Cas and *Dat files, also can first through FLUENT guide a certain surface variable, set into a format document input to Tecplot.

3.4 Contact angle and boundary conditions

The VOF method needs to take the contact angle as the boundary condition, and the dynamic change of the contact angle is very important. There are three contact angle models for droplet contact angle changes in the process of motion, which are static contact angle model (SCA), dynamic contact angle model (DCA) and mesh change contact angle model (MDCA).This paper mainly simulates the impact force of droplets on the wall surface, so the static contact angle model is selected to meet the simulation requirements. In order to save calculation time, the left boundary is set as symmetric boundary, and the upper boundary and the right boundary are set as open boundary.

3.5 Solver selection

Fluent solver provides two numerical methods, separation solution and coupling solution. The separation solver is a pressure-based solver. The specific solving process is as follows: instead of directly creating simultaneous equations, a single governing equation is solved one by one sequentially, that is, an equation such as U momentum equation is solved on the whole grid, and then another equation such as V momentum equation is solved. Since the governing equations are nonlinear and coupled to each other, iterative calculation is required before the convergent solution is obtained, and the separation solver only adopts the implicit scheme to linear the governing equations. Coupling solver is a density-based solver. Its specific solving process is as follows: simultaneously solving the coupling equations of continuity equation, energy equation, momentum equation and component transport equation, and then solving the scalar equations of turbulence one by one; the governing equations are nonlinear and coupled to each other, multiple rounds of iteration are needed before the convergence solution is obtained. The coupling solver can adopt implicit or explicit schemes to linear the governing equations. Separated-solver is suitable for solving incompressible and slightly compressible fluid flow problems. By solving the discrete equations of momentum equation and continuity equation simultaneously, the velocity component and the corresponding pressure value can be obtained directly. Coupling calculator is used to calculate the high speed compressible fluid flow problem. The velocity component and density are taken as the basic variables of the equation, and the pressure value is solved through the state equation. This paper numerically simulates the droplet impact force problem, so the pressure-based calculation solver is chosen.

3.6 Calculate region initialization

In this paper, the initial distribution of each phase fluid is set as follows: firstly, the whole calculation grid area is initialized. The air phase is defined as the main phase with the initial volume integral of 0, and the water with heavier density is defined as the second phase with the volume fraction of 1, so that the whole calculation area is filled with air and gas phase, i.e., the volume fraction is 0.After initialization, the spherical position area occupied by the initial droplet was marked at the bottom of the wall with the function of Adapt Region in FLUENT. Finally, the volume fraction of this region is given as 1 through Patch function, which indicates that it is the second phase water. The initial droplet shape can be observed by displaying the phase diagram. And then define the impact velocity of the droplet in the Y direction.

3.7 Impact force report definition

When defining the report of impact force, the normal direction of impact force is in the Y direction. Select the bottom of the action plane, and then select the output DAT file. Since the left boundary is symmetric, the impact force should be twice the output file, and the impact force can be multiplied by twice in the report expression

3.8 Calculate stability and convergence

The size of the time step will have an impact on the convergence and stability of the calculation, so it is necessary to find the most reasonable selection of the time step through constant debugging in the calculation process. The size of the time step is mainly selected according to the Courant number to meet the convergence and stability of the calculation. Generally speaking, the convergence rate of Courant number is slow when the Courant number is small, but the stability is good. When the Courant number is large, the convergence rate is fast and the computational stability is poor. In the calculation, the Courant number was adjusted by observing the convergence speed and stability of residuals and selecting appropriate time step. In this paper, the time step was selected as 1e-6, Courant number C is 0.0266.

$$C = u\frac{\Delta t}{\Delta x}$$

Where u is the fluid velocity, Δt is the number of time steps, Δx and is the mesh size.

Chapter 4

Results

4.1 Droplets impact the hydrophobic surface

Fig4.1 shows the dynamic process of the droplet impacting on the hydrophobic solid wall at a height of 10cm. Because the shearing force of the air on the droplet at low speed is negligible, the droplet always keeps a regular spherical shape before hitting the wall. Under the action of inertial force, the dynamic friction force and adhesion force of the droplet on the wall surface extend along the radial direction and gradually move to the maximum spreading diameter.

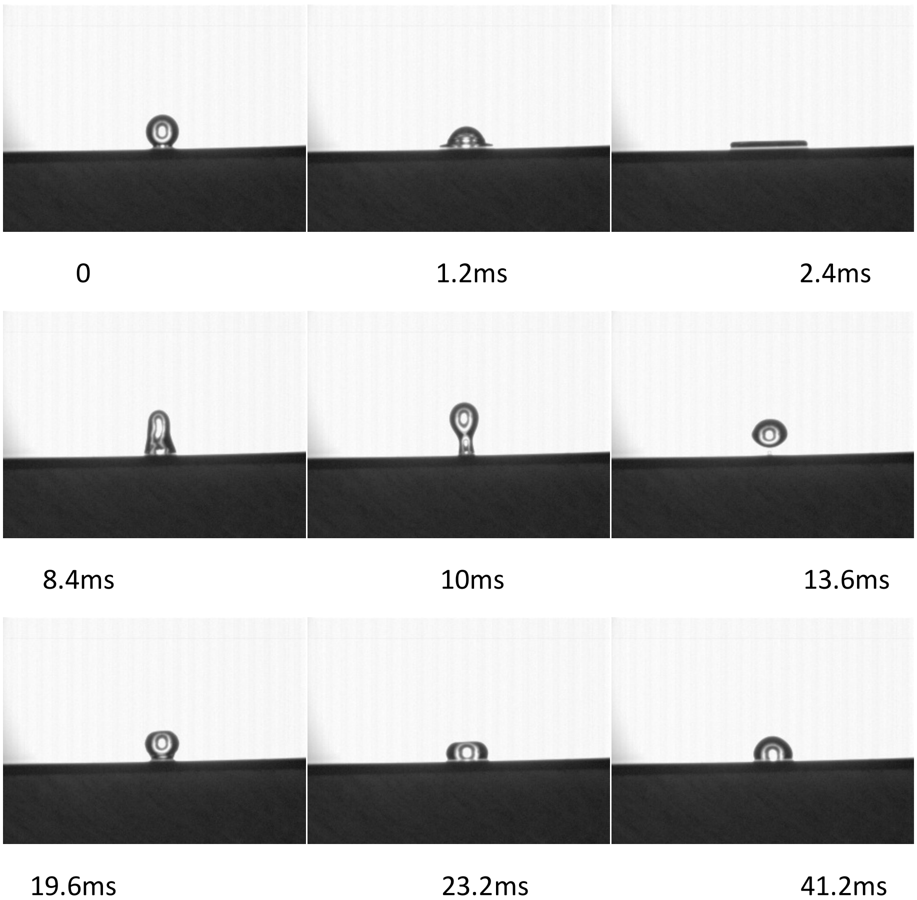


Fig4.1 droplet falling at a height of 10cm hitting a hydrophobic solid wall

In the process of droplet spreading, the kinetic energy of the droplet is gradually transformed into the surface energy and dissipated energy of the droplet spreading. In Fig4.3, when the maximum spreading diameter is reached, the kinetic energy of the droplet is zero, and the surface energy possessed by the droplet is far greater than that possessed by the static droplet when it spreads its final state on the same surface. The droplet is in an unbalanced state, and the droplet will move in the direction where the surface free energy decreases. Driven by the surface tension, the droplet will overcome the wall dynamic friction and the adhesion force retraction. In this process, the surface energy of the droplet will be converted into kinetic energy and dissipated energy of the droplet. When the energy converted is greater than the sum of the energy dissipated in the retraction process and the initial surface energy of the droplet, the excess energy will make the droplet rebound from the wall. As the retraction movement continues, a smooth salient column appears at the center of the liquid film and then gradually forms a bowling bottle shape by the surface tension and the extrusion of the surrounding liquid. The droplet under the effect of surface tension and inertia force keep rising movement trend, because the surface of the droplet adhesion force will block at the bottom of the droplets from the wall, and the upper part of the droplets free surface will continue to rise, makes the droplet gradually stretch into the form of liquid column and the surface tension and surface adhesion force, under the coupled action of droplet elongated to longitudinal maximum length, eventually the droplets bounce off the wall. After detaching, the droplet continues to move under the action of gravity and surface tension. The surface tension drives the droplet to change to the form with the minimum surface energy. As a result, the longitudinal length of the droplet decreases gradually. Because of the inertia, the droplets will not be directly transformed into a stable ball, but form a symmetric, and along the horizontal and vertical direction of the counter-oscillation, similar to the creep of the movement of the square. When the droplet rises to the highest point, its kinetic energy is completely transformed into gravitational potential energy, surface energy and dissipated energy, and the droplet drops again in a creeping form under the action of gravity, hitting the wall surface.

4.2 Droplets impact the hydrophilic surface

As shown in Fig. 4.2, after the spherical droplet hits the hydrophilic surface, it spreads to the maximum spreading diameter under the action of gravity and presents a concave shape at the top. The kinetic energy of the droplet is transformed into the surface energy of the liquid film and the viscous dissipation during the spreading process. The next moment the top of the droplet oscillates under surface tension until it comes to rest.

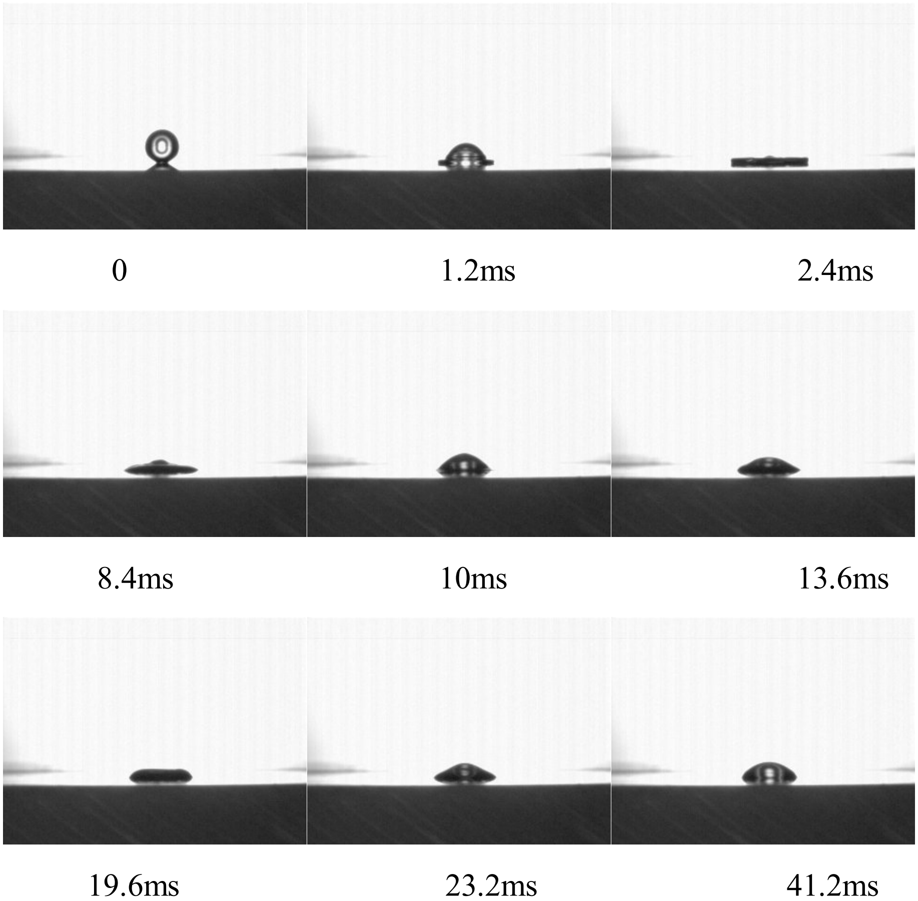


Fig4.2Droplet falling at a height of 10cm hitting a hydrophilic surface

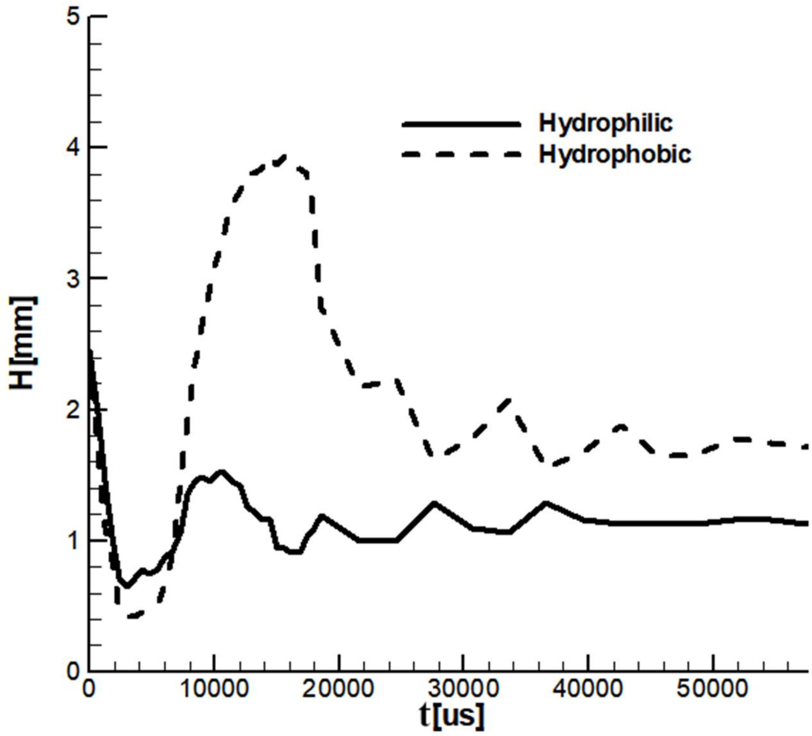


Fig4.3The height of the droplet varies with time

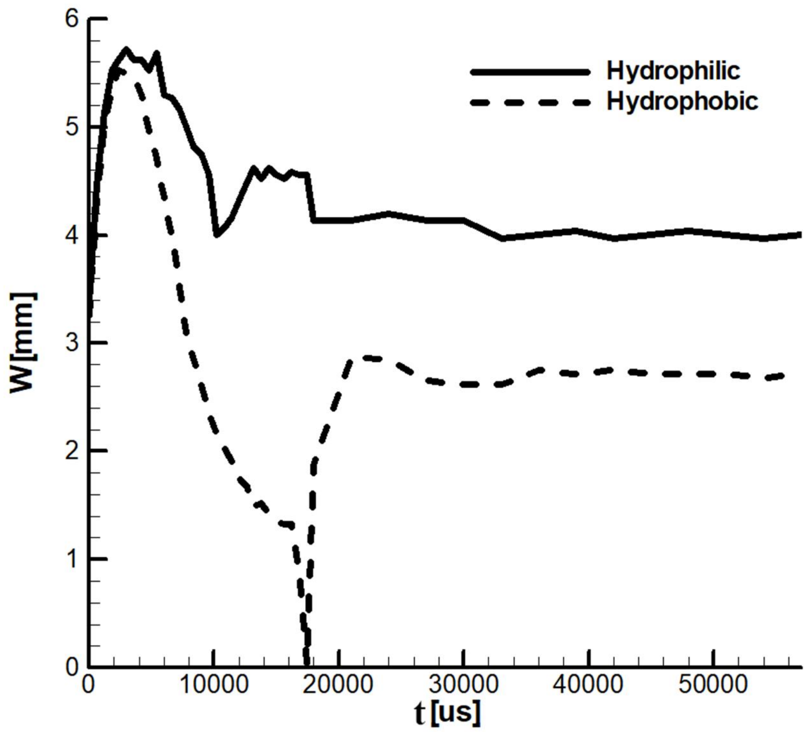


Fig4.4The width of the droplet varies with time

By comparison, it can be seen Compared with the spreading process of hydrophobic surface, the droplets bounce higher off the hydrophobic surface and leave the wall at 260 steps, the hydrophilic surface has the characteristics of larger spreading diameter and lower center of gravity in the final state due to its low equilibrium contact angle.

4.3 Simulation results with the Navier-Stokes Equation

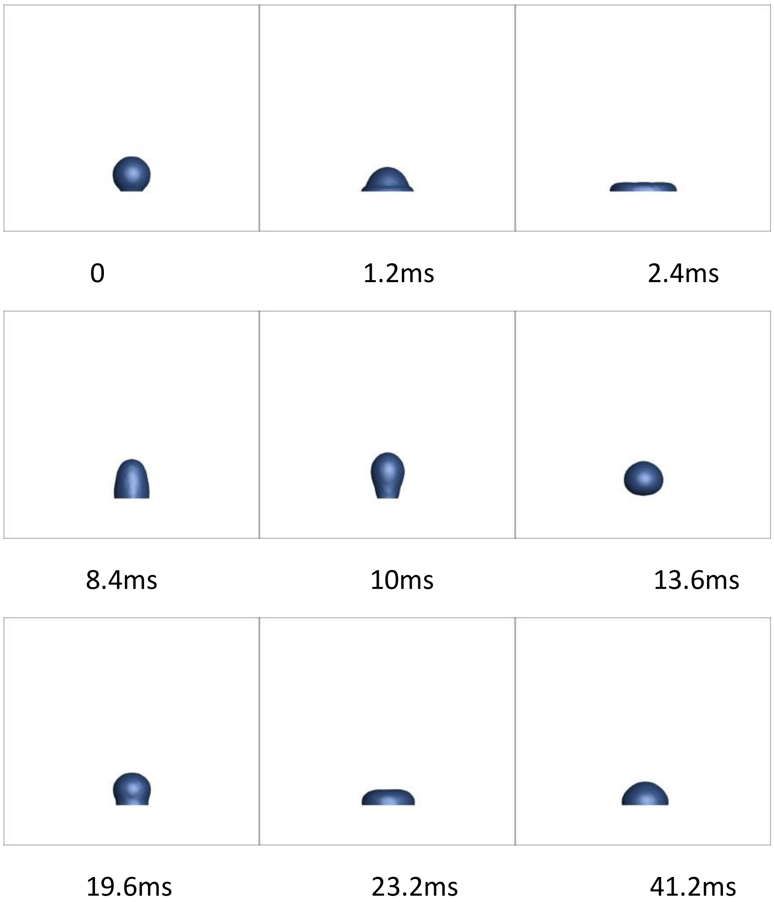


Fig4.5 Droplet falling down to the bottom plate(shown left upper to right down)

4.4 Comparison of experimental and simulation

Fig 4.6 shows the three-dimensional collision shape process of a droplet with a radius of 1.2mm impacting on the glass surface at a speed of 0.99m/s. The contact angle between the droplet and the wall is 100°, and the surface tension coefficient is 0.072N/m.Droplets in contact with the wall when the time is 0, it can be seen that the droplets remain the ball when first contact surface, and then spread out from the bottom and reached maximum spreading diameter about 2.4 ms, in under the action of surface tension, drops into the stage of retraction, and again in 13.6 ms away from the wall, after 35.2ms drops to fall on the wall, and achieve steady state,The comparison between the two figures shows that the experimental results are basically consistent with the simulation results.

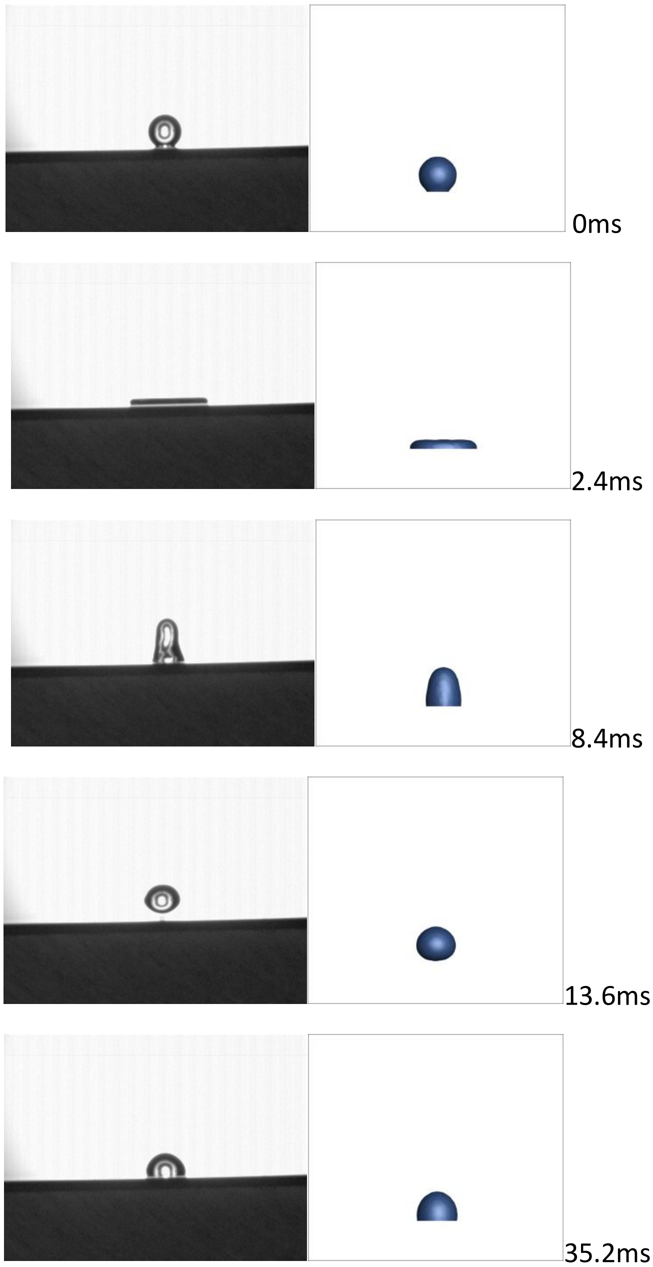


Fig 4.6 Falling process of a droplet

4.5 Width comparison between simulation and experiment

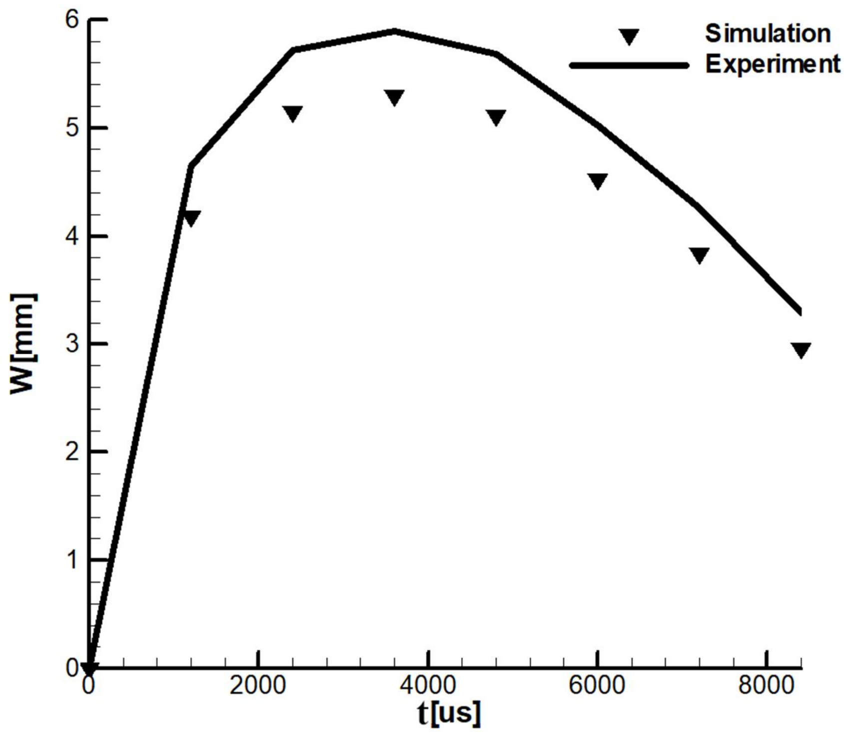


Fig 4.7 Spreading width with time

The experimental and numerical values were calculated by using water droplets with a straight diameter of 1.2mm and a collision velocity of 1m/s, and comparing the spread number with the change of time, as shown in Fig 4.7.The contact angle between the droplet and the wall surface in calculation is 100°.It can be seen from the figure that the numerical simulation results are close to the actual results. The spreading coefficient of fruit calculated by numerical value is lower than the experimental value, and the time to reach the maximum spreading width is later than the experimental value. The maximum droplet spreading width of the numerical simulation is 5.8mm, while the experimental maximum spreading width of the actual data is 5.2mm.

4.6 Height comparison between simulation and experiment

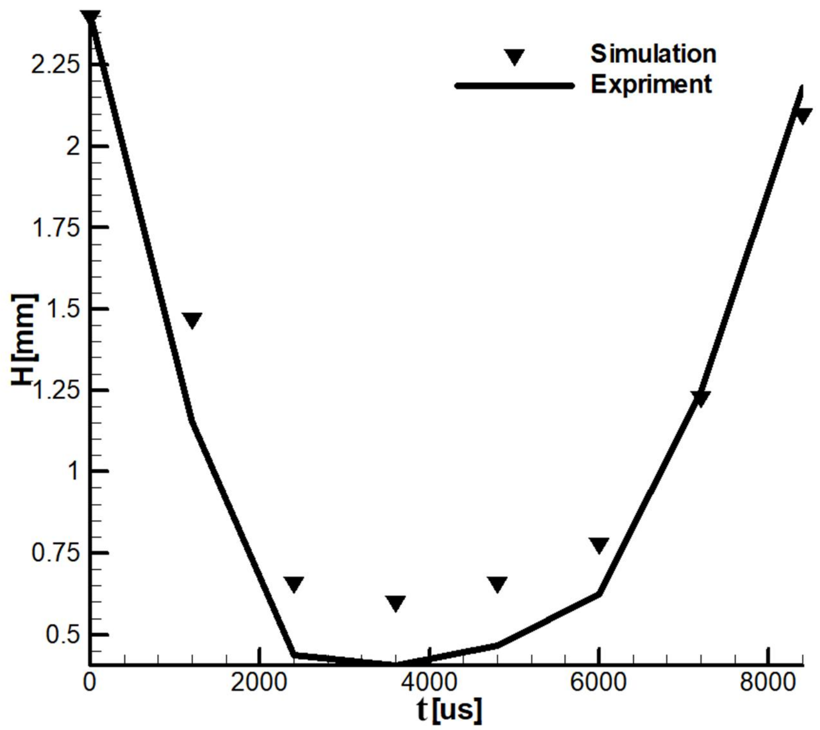


Fig 4.8The droplet height varies with time

Figure 4.8 shows the change of droplet bounce back height with time. Same as the spreading coefficient, the experimental value is larger than that in simulation. The experimental height to reach the minimum is 0.2mm, while the simulated height is 0.6mm,

In general, the curve change rule of the experiment and the simulation is basically the same, so the numerical model can better simulate the droplet collision process, so the numerical model is used to study the change rule of the droplet collision force on the wall.

4.7 Impact force of droplet impact on dry surface condition(Experiment)

The collision phenomenon between liquid drops and solid wall is widely existed in natural boundary, daily life and industrial and agricultural production, such as raindrop scouring of soil, ink jet printing, pesticide spraying, jet cutting, spray axial flow fan and the impact of water droplets on blades in wet steam stage of steam turbine. In the course of liquid-solid collision, the transient collision force between the droplet and the wall surface is the key factor of droplet shape change and droplet erosion.

In order to analyze the shadow response of different wall surfaces to the impact force F, the hydrophilic of the plane was changed while the droplet diameter was kept unchanged. In calculation, the straight diameter of liquid drops is 4.64mm, the degree of impact velocity is 2.8m/s, and the contact angle is 10° and 90°.The super-hydrophilic plane is realized by hydrophilic spray. The hydrophilic spray is shown in Figure 4.9. Impact forces of different surfaces are shown in Figure 4.10,4.11.

Fig 4.9 Super-hydrophilic spray

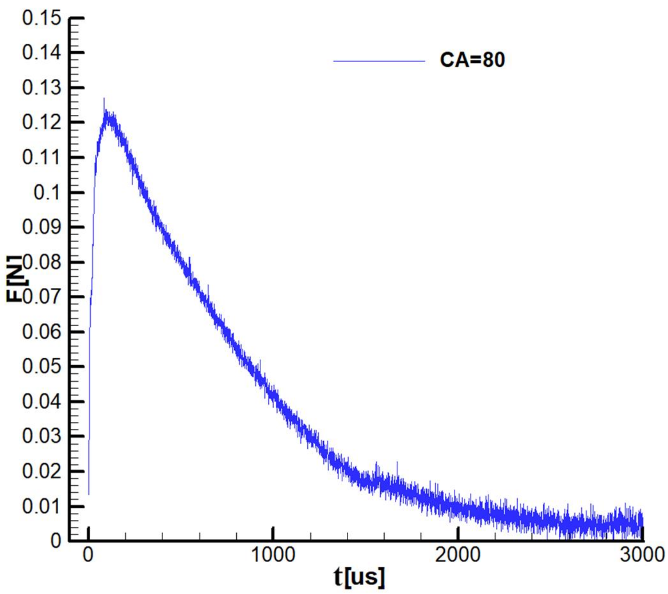


Fig 4.10 Impact force of hydrophilic surface

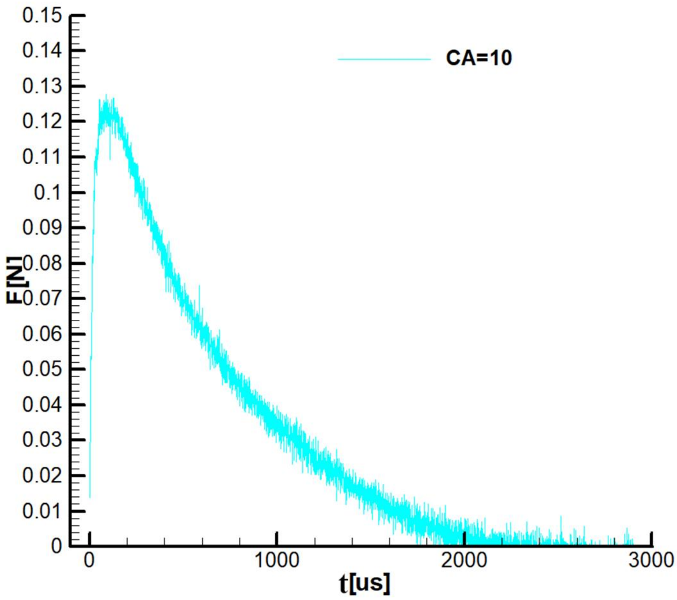
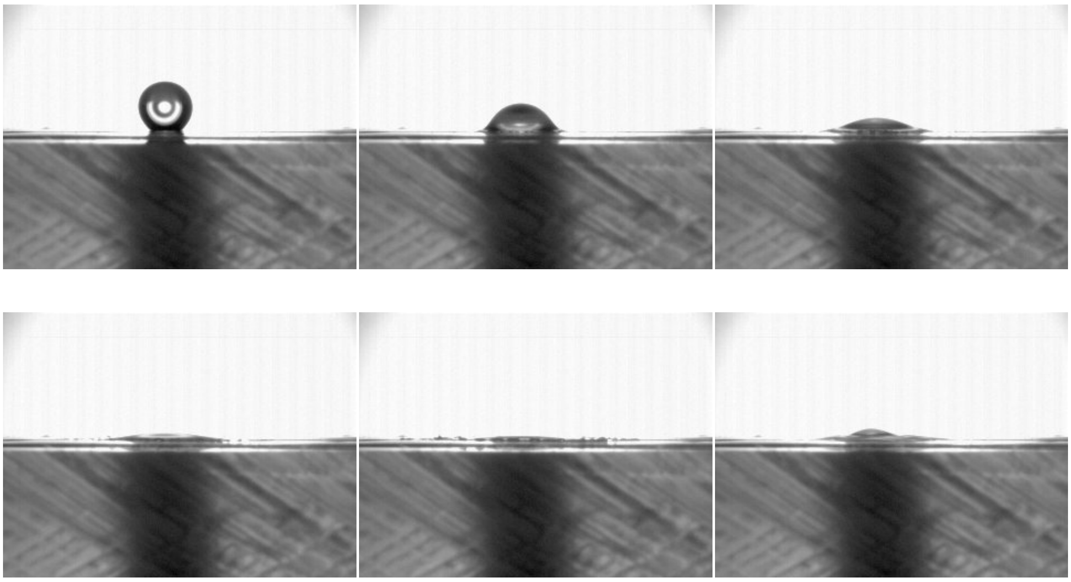


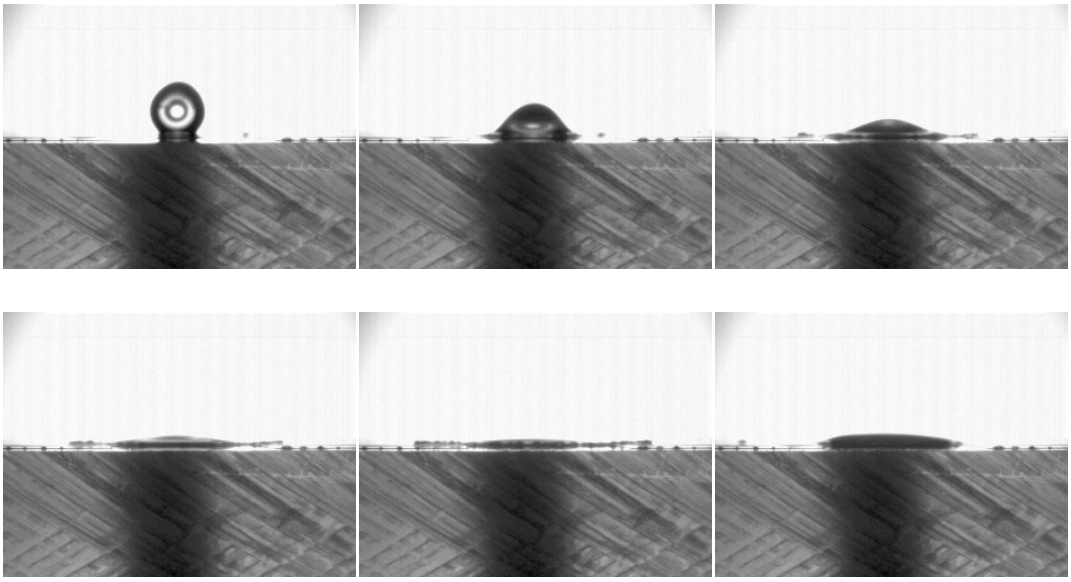
Fig 4.11 Impact force of super-hydrophilic surface

Above the droplet impact the impact force curve of different wall, daub on flat at the bottom of the water spray, static, surface contact angle80°, the basis of the daub after spraying the surface contact angle of 10°, the results of the two wall are calculated respectively three times, then the average, comprehensive analysis shows that two kinds of material's influence on the droplet impact is not big, to base on the wall of force relative to the hydrophilic wall force is small. As can be seen from the figure, the impact force of the droplet all occurs in the droplet diffusion stage. The maximum of droplet diffusion is influenced by the wall surface and the process is similar.

The following figure shows the whole process of the droplet impacting on two different wall surfaces. When the droplet reaches the steady state, the contact angle does not return to 80° when the droplet reaches the steady state on the hydrophilic wall surface. Because the Weber number is too large, the droplet falling is mainly affected by the image of inertial force, the surface tension becomes smaller, the droplet retracting is difficult, and the Froude number is relatively large, and the droplet is also prone to breakage.



Hydrophilic



Super-hydrophilic

Fig 4.12The process of droplet spreading on two wall surfaces(When the droplet contacts the wall, T left to right is 0,600us,1200us,1800us,2400us,3200us)

4.8 impact force of droplet impact on liquid film

Figure4.12 is the study on the impact of liquid drops on solid walls. In the real industrial field and the field of life, it is also a common phenomenon that liquid drops impact on liquid film.Liang Gangtao, Guo Yali and Shen Shengqiang [25]established the physical and mathematical model of a single droplet impacting on a plane liquid film, numerically simulated the phenomenon of a droplet impacting on a plane liquid film by using the Couple Level Set and Volume of Fluid method, and analyzed the jet generated after the impact. The neck jet is mainly caused by the large local pressure difference in the neck region after impact, and the radial movement of the fluid in the liquid film helps the jet to develop into coronal spray. The droplet hits the liquid film as shown in the figure4.13

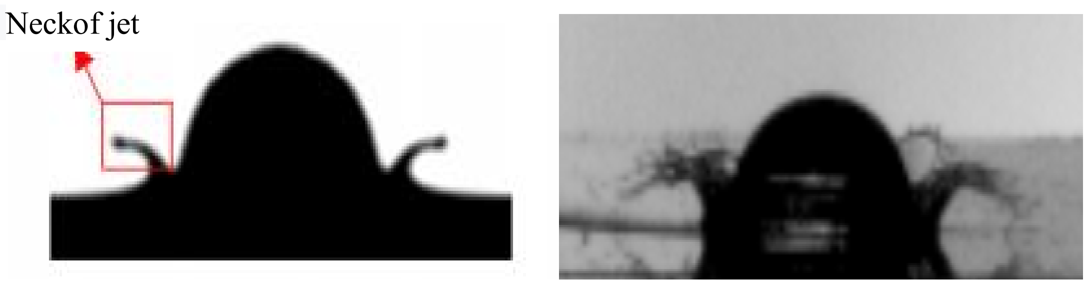


Fig 4.13Jet flow phenomenon（left from reference paper, right from experiment）

Guo jiahong and Dai shiqiang [26] using the method of experimental observation on the splash phenomenon after the impact of liquid droplets liquid film was studied, the following conclusion, the viscosity of the liquid and the surface tension of the splash and splash have inhibitory effect. With the increase of liquid film thickness, the splashing phenomenon of droplet impact is weakened.

Fig 4.14splash phenomenon（left from reference paper, right from experiment）

In this paper, the experimental method was adopted to striking the droplets on the liquid film impact force are studied, the experimental total cent two kinds, the initial state, as shown at left for before falling droplets, a layer of liquid film is formed on the wall, liquid film is produced by water spray onto wall super hydrophilic phenomenon caused by, the right to use the spray, the size of two figure of liquid film is the same size, different height.

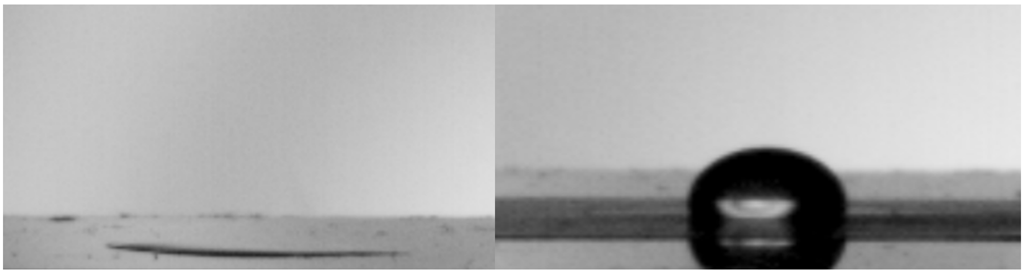


Fig 4.15Liquid film initial state

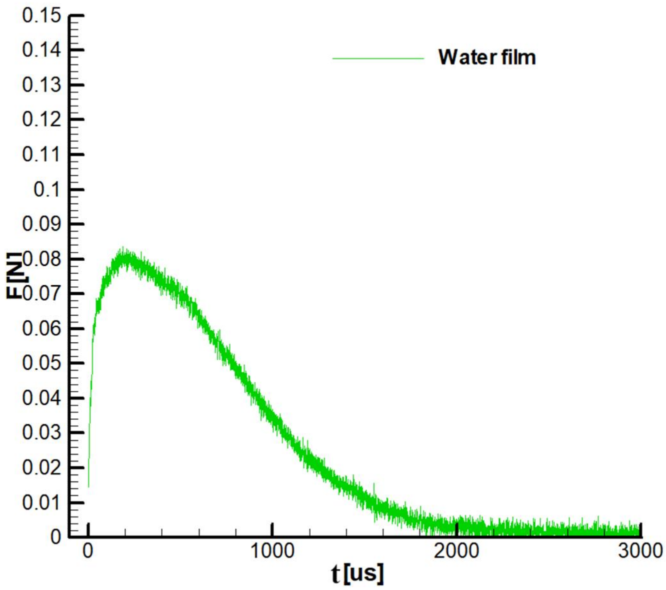


Fig 4.16The impact force of a droplet on a film of water

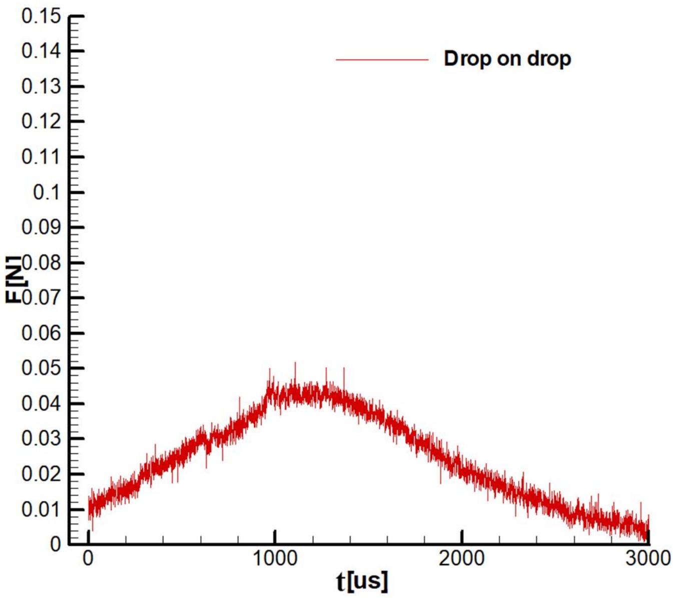
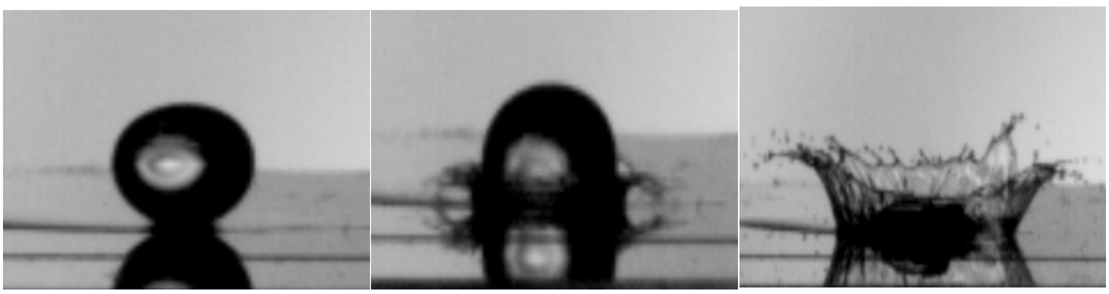


Fig 4.17The impact force of a droplet on a drop

Drop impact curve of different wall above, daub is on a flat at the bottom of the water spray, then drop a drop of liquid droplets on the surface, two kind of wall thickness of liquid film is different, the result of the droplets hitting a wall are calculated respectively three times, and then the average, comprehensive analysis shows that the two kinds of materials have bigger influence on the droplet impact, droplet impact in the liquid film thickness of thin wall, The maximum impact force is larger, and the force on the wall with thicker liquid film is smaller, but the impact force is larger in the stage of impact force reduction.



Water film

Drop on drop

Fig 4.18The process of droplet spreading on two surfaces(When the droplet contacts the wall, T left to right is 0,1000us,2000us)

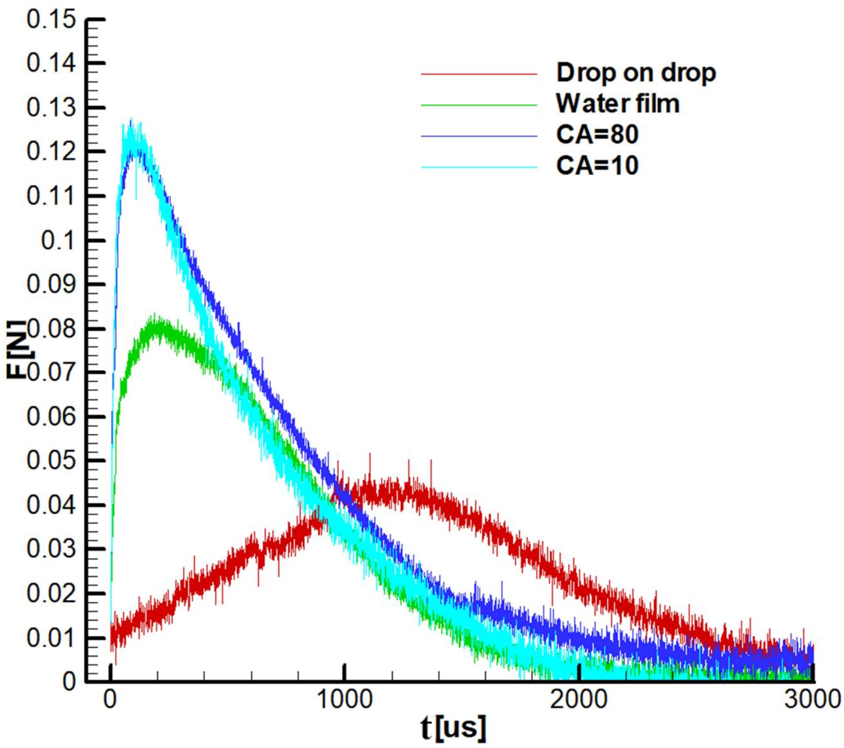


Fig 4.19 Comparison of impact forces in different conditions

Above four wall for droplet impact the impact force of contrast, the impact is not big different contact Angle on the peak value of impact force, the impact force decrease phase, the contact Angle greater force larger droplets, and wall after adding liquid membrane, droplet impact force decreased significantly, and the droplet impact force decreases with the increase of the thickness of liquid film, but the shock stage, the thicker the liquid film force is greater.

4.9 Numerical calculation method of droplet impact force

Because of the symmetry of droplet collision process, a three-dimensional symmetric model is used. The length, width and height of the cube are respectively W=10mm (x) x 6mm (y) x 10mm (z).The boundary element of the solution region is left boundary is the axis of symmetry, the lower boundary is the wall surface, the droplet surface is the free surface, and the other boundary is the atmospheric environment. The effect of gravity was taken into account in the calculation. At the initial moment of calculation, a distance of 1mm was set between the droplet and the wall surface to consider the influence of the presence of air on the free surface of the droplet. The coupling calculation method of pressure and speed was PISO. The number of overlapping times in each time step was selected as 20 times, and the step size between time periods was calculated as 1e-6s.

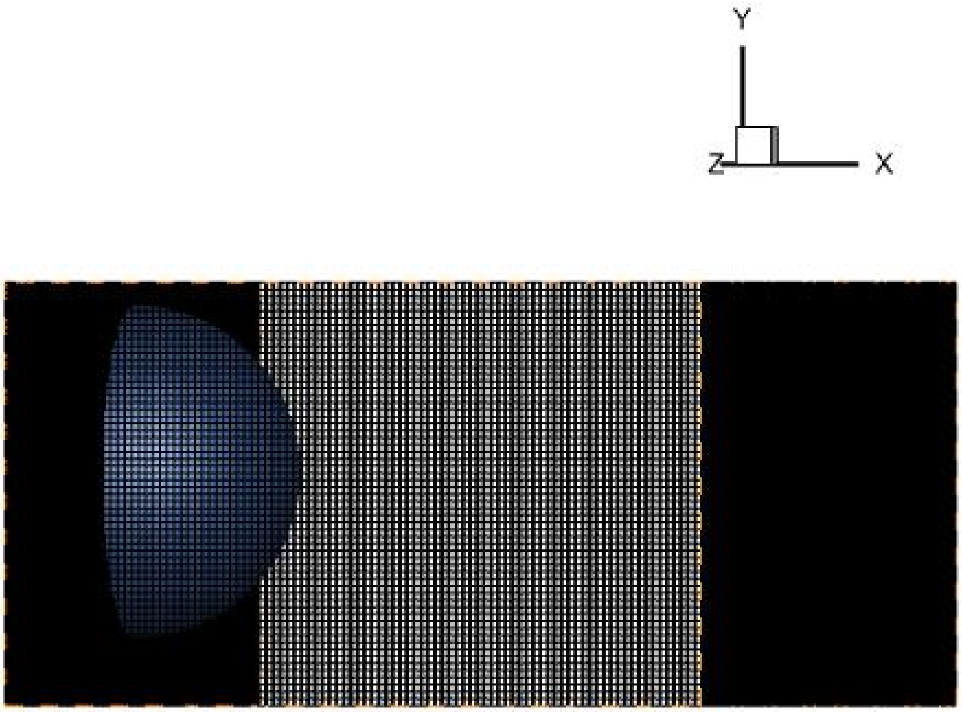


Fig 4.20 Computational domain

4.10 Verification of mesh

The finer the mesh is, the greater the impact force is. In this paper, the impact force with mesh sizes of 0.14, 0.12, 0.1, 0.08 and 0.06mm is simulated. The maximum difference of the five mesh sizes is 0.005N. In order to calculate the stability, and combined with the actual situation of the computer, so 0.1mm mesh was used in this article.

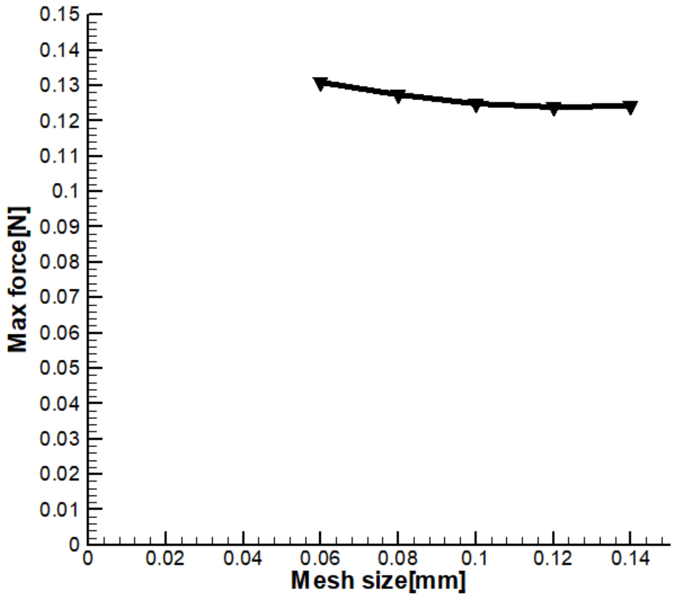


Fig 4.21 Peak impact force of different meshes

Below is compared with the reference papers[27], we can see that under the same parameters, the collision force curve of the droplets is almost consistent with that in the reference papers will experiment and simulation, and the result is almost the same, so this model is used to monitor the change of the collision force is feasible, and the numerical method in change the shape of liquid droplets form collision and other parameters also have more advantages.

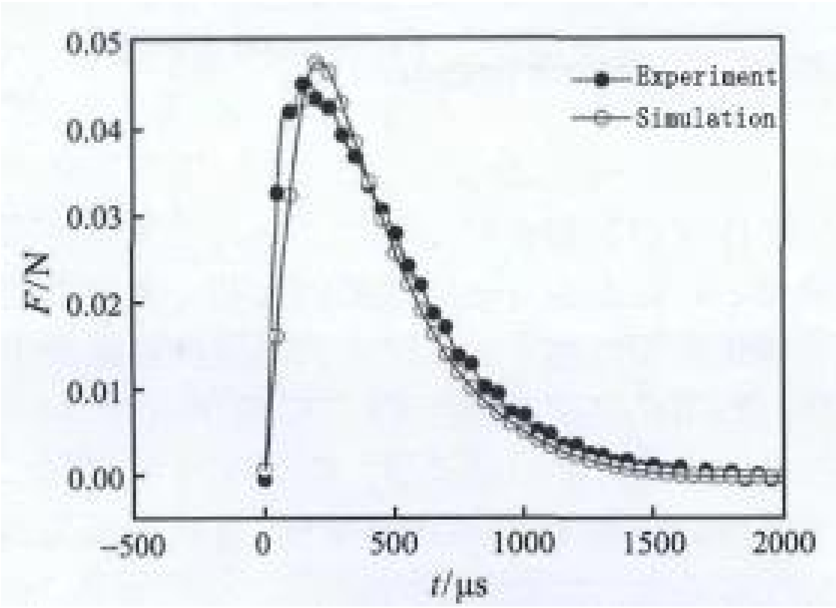


Fig 4.22 Comparison of the simulated and experimental results of the impact force of water droplets

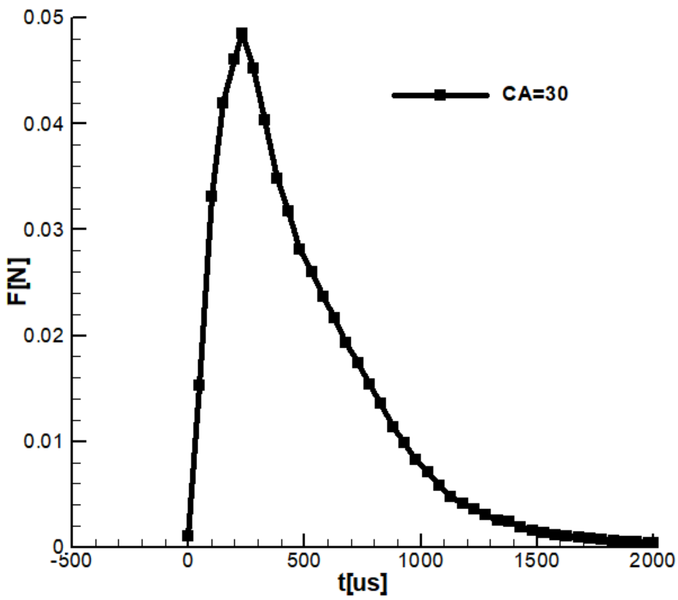


Fig 4.23 Simulation of droplet impact force

According to the figure 4.23, the diameter of the water drop is 2.7mm, the impact velocity is 2.67m /s, and the contact angle between the water drop and the wall surface is 30°. The contact time between the water droplets and the solid wall surface is0us.

4.11 Influence of contact angle on impact force

According to paper [28],It is proposed that the droplet impact force is not affected by the contact angle, so the impact change is simulated when the contact angle between the droplet and the wall is 100°.

As can be seen from the figure, the impact force at different contact angles all reached the peak at 300us, and the change of impact force with time was basically consistent, indicating that the change of contact angle had little influence on the impact force and the collision process.

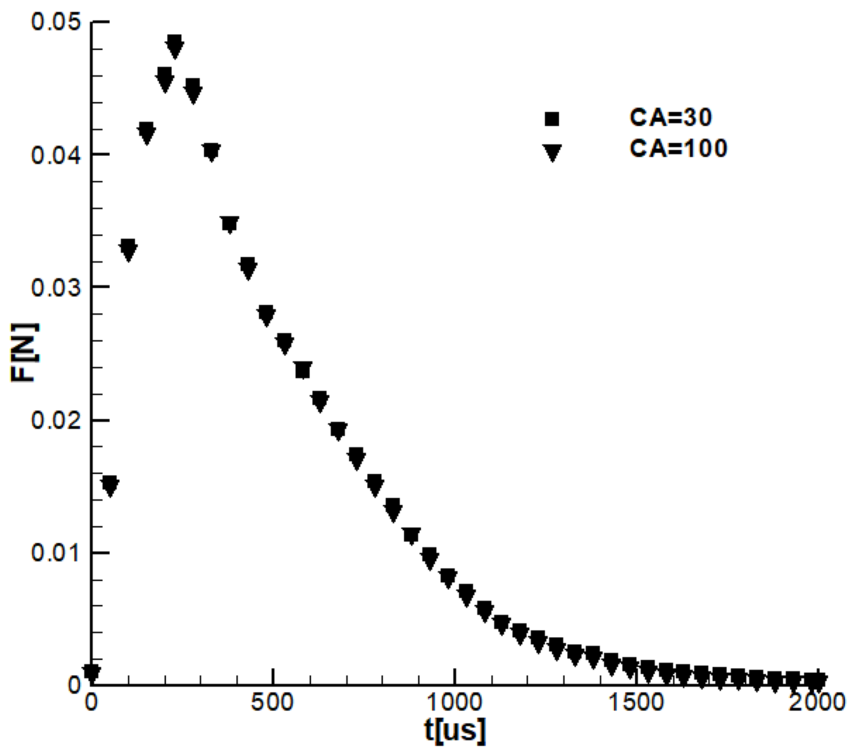


Fig 4.24 Impact force at different contact angle with time

4.12 Influence of droplet diameter on impact force

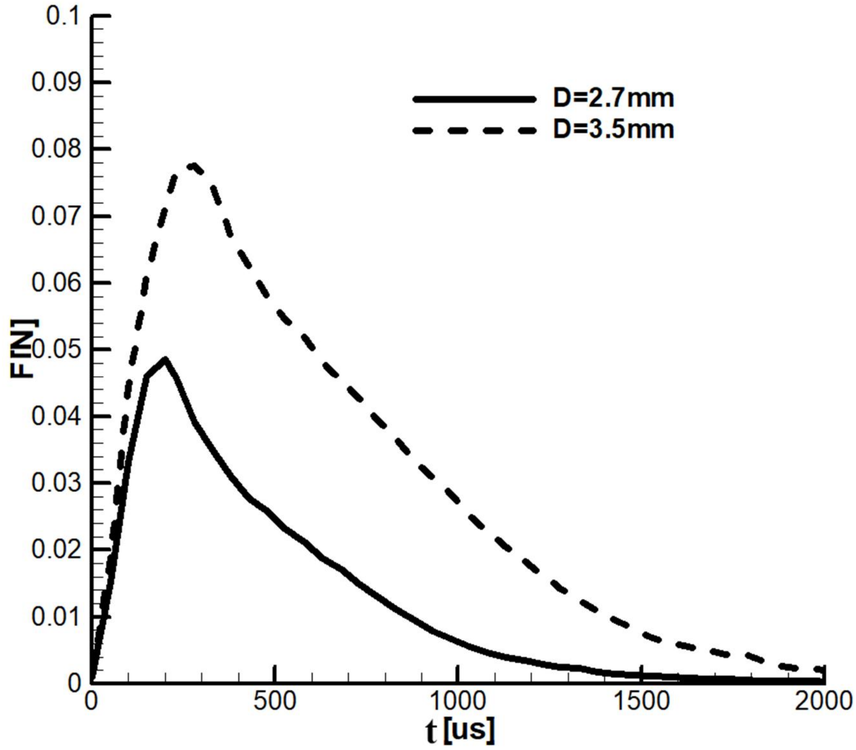


Fig 4.25Impact force at different droplet diameter with time

In order to analyze the impact of droplet diameter changes on the collision force, the velocity was kept at 2.53m/s, and the droplets with diameters of 2.7mm and 3.5mm were simulated, and the contact angle between the droplets and the wall was set at 30°.

The change of impact force is shown in the figure. For droplet with large diameter, the larger the peak value of the impact force on the wall, the shorter the time to reach the peak value of the impact force, and the slower the decline rate

4.13 Influence of velocity on impact force

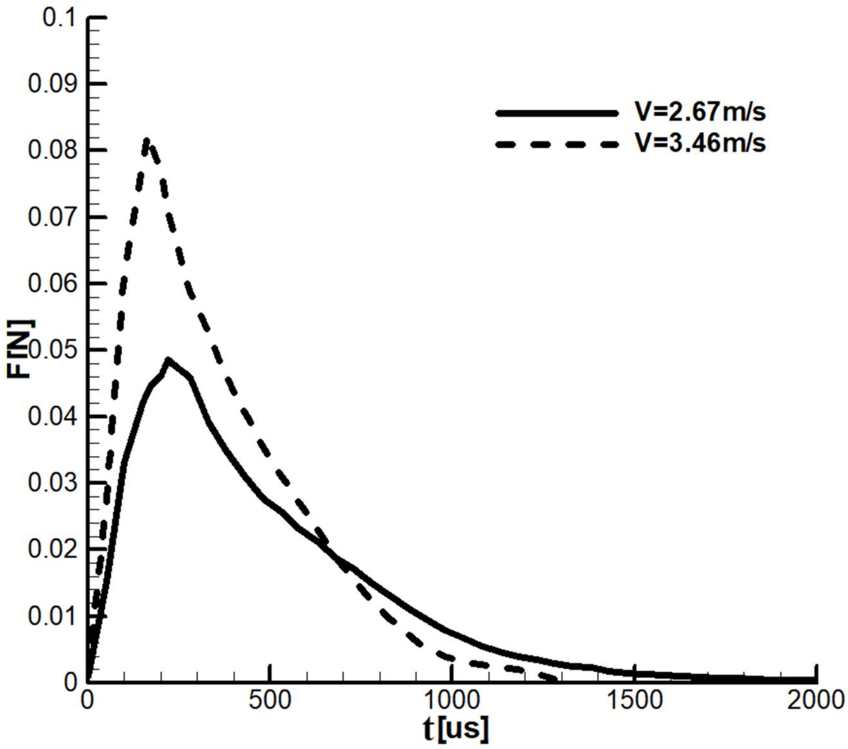


Fig 4.26 Impact force at different velocity with time

It can be seen from the figure that with the increase of the impact velocity, the peak value of the impact force increases, and the shorter the speed to reach the peak value of the impact force.

In all of the impact force simulations, the calculated impact force has a small initial value at time 0, because in the process of the droplet being set down from the initial position, Its impact on the air near the wall surface increases the air pressure between the droplet and the wall surface, resulting in non-zero pressure at the wall surface.

4.14 Influence of different boundary on impact force

In Fluent simulation, there are two boundaries of slip and no slip at the bottom. With other parameters unchanged, the two kinds of boundary were simulated respectively. According to the figure, the peak value of impact force is greater at the non-slip boundary, and the impact force at the slip boundary is greater at the stage of impact force reduction, because the viscous force of droplets on the slip boundary tends to be 0N, and the diffusion speed of droplets on the slip boundary is faster.

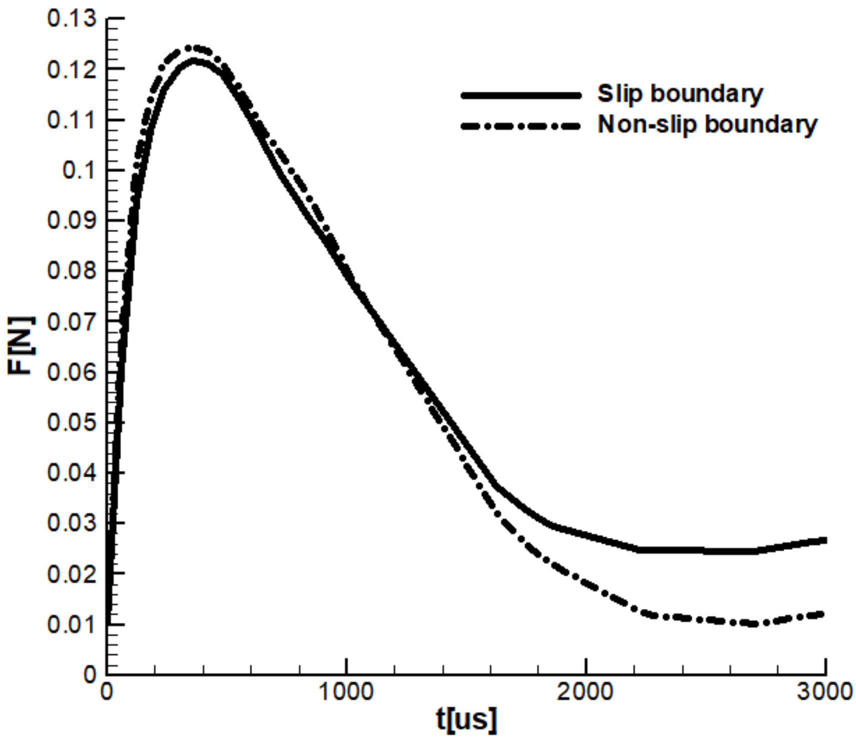


Fig 4.27 Simulation comparison of the two boundaries

4.15 Experimental and numerical comparison of impact forces

The following figure shows the change curve of impact force simulated. Judging from the peak value of impact force, the slip boundary is closer to the experimental result. Therefore, in the simulation of Fluent, it is more consistent with the actual situation to use the slip boundary at the bottom.

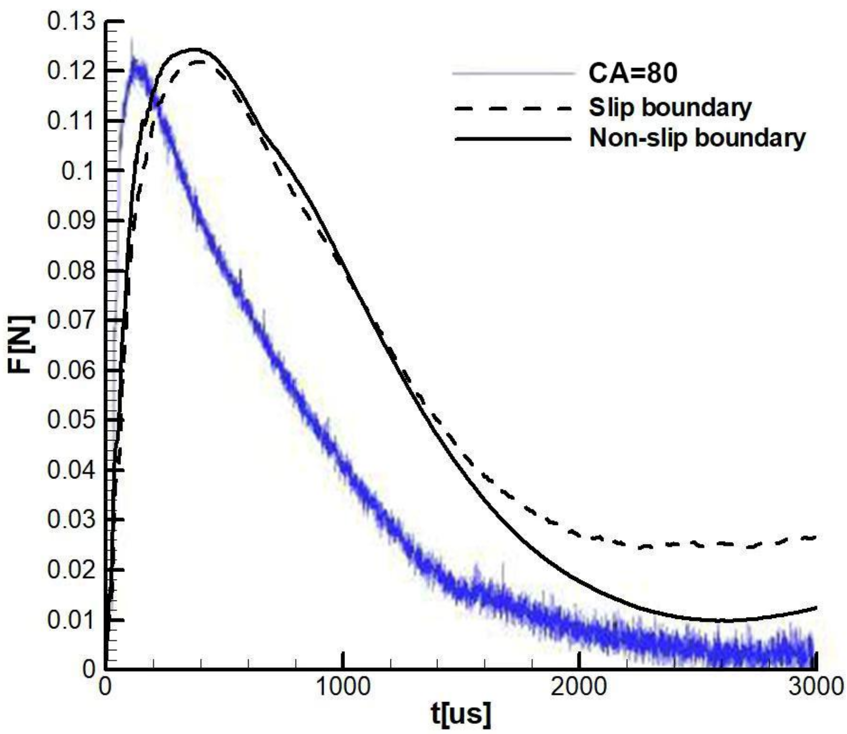


Fig 4.28 Comparison of Experimental and simulated

Chapter 6

Conclusions

In this paper, experimental and simulation methods were used to observe and compare the spread and rebound and impact force of droplets.

Firstly, the impact characteristics of a 1.2mm droplet at -0.99m/s were numerically simulated by the experimental method and the VOF method. The droplet has same process of spreading first and then rebounding. However, at high Weber number, the droplet surface tension becomes smaller, and the droplet is broken after impact, and cannot return to the static height

Secondary, The impact forces of droplet impinging on four different wall surfaces are measured experimentally. When the droplets impact the dry wall, the results show that there is little difference between the two results. And experimental method was used to simulate the impact force of droplet impinging on different wall surfaces with or without liquid film. The thickness of the liquid film has a greater influence on the impact force. When the hydrophobic liquid film is hit with the same velocity, the force is reduced by about 50% compared with that of the hydrophilic liquid film.

Thirdly, Fluent was used to simulate droplets of different sizes and impact velocities impact the same wall surface. The greater the diameter and velocity, the greater the impact force.

Finally, By comparison of experiment and simulation, we can know that the slip boundary is more suitable for the study of impact force.

References

[1] Young T.1805, “An essay on the cohesion of fluids”, Philos Trans R Soc London, 95 65-87.

[2] Worthington A.M.1876.“On the forms assumed by drops of liquids falling vertically on a horizontal Plate”, Proc R Soc London, 1876, 25 261-272.

[3] Josserand.C and Thoroddsen S. 2016,“Drop impact on a solid surface”. Annual review of fluid mechanics, 2016, 48 365-391.

[4] KwonD.H and Lee S.J. 2012, “Impact and wetting behaviors of impinging microdroplets on superhydrophobic textured surfaces”, Appl. Phys. Lett, 100(17) 171601.

[5] Yarin A.2006, “Drop impact dynamics: splashing, spreading, receding, bouncing.... ”nu. Rev. Fluid Meeh, 38 159-192.

[6] Tsai P, Pacheco S, Pirat C,2009.et al. “Drop impact upon microand nano-structured super-hydrophobic surfaces”, Langmuir, 25(20) 12293-12298.

[7] Worthington A M,1908, “A Study of splashes,Long mans,Green,and company”.

[8] Collings E W, Markworth A J,Mccory J K. Slpatquench, 1990,“solidification of freely falling liquid drops by impact on a planar substrate.Journal of materials science”,25:3677-3682.

[9] Chandra.S,Avedisian.C.T,1991, “On the collision of a droplet with a solid surface”,Proceedings:Mathematical and Physical Sciences,432:1341.

[10] PasandidehFard M,qiao Y M,Chandra S, et al.1996, “Capillary effects during droplet impact on a solid surface.Physics of Fluids”,8(3):650-660.

[11] Ukiwe C,Mansouri A,Kowk D Y, 2005, “The dynamic of impacting water droplets on alkanethiol selfassembied monolayers with coadsorbed CH3 and CO2H Terminal groups”.Journal of colloid and interface science, 2005,285(2):760-768.

[12] Marchandise E,Remacle F, Chevaugon N,2006, “A free discontinuous Galerkin method for the level set equation.Journal of computational physics”,2006,212:338-357.

[13] Hughes T,Liu W,Zimmermann T,2006, “Lagrangian Eulerian finite element formulation for incompressible viscous flows”,Computer methods in applied mechanics and engineering”,1981,29:239-349.

[14] Liang Chao, Wang Hong, Zhu Xun, et al,2013, “Numerical simulation of dynamic process of droplet impinging on different wetting walls”,Journal of Chemical Industry and Technology,2013,64(8):2745-2751.
[15] Gunjal P R,ranande V V,chaudhari R V, 2005,“Dynamics of drop impact on solid surface:experiments and VOF simulations”, merican Institute of Chemical Engineers Journal,51(1):5978.
[16] Zheng Zhiwei, Li Dashu, Qiu Xingqi, et al,2015, “Numerical Analysis of Level Set VOF Method for Complex of Spherical Concave Surface by Droplet Impact”,Chemical Engineering Journal,66 (5):1667-1675.
[17] Raman K A,Jaiman R K,Leet S, et al,2016, “Lattice Boltzmann simulations of droplet impact onto surfaces with varying wettabilities”, International Journal of Heat and Mass Transfer,95:336-354.
[18] Liang Chao,2013,“Numerical Study on Dynamic Characteristics of Small Droplet Impacting on Solid Wall and Thin Liquid Film”,Chongqing: Chongqing University.
[19] Bussman M,Mostaghimi J,Chandrs S,1999, “On a Three-dimensional Volume Tracking Model of Droplet Impact”, Physics of Fluids,11(6):1406-1417.
[20] Wang Y X,Chen S,2015, “Numerical Study on Droplet Sliding across Micropillars”angmuir,31 (16): 46734677.
[21] Chen Yuanyuan, 2017, “Numerical Simulation of Droplet Collision-hydrophobic Combination Wall Process”, Beijing: North China Electric Power University.
[22] Li R, Hisashi N, Michitsugu M,2011, “ A numerical Study of Impact Force Caused by Liquid Droplet Impingement onto a Rigid Wall”, Progress in Nuclear Energy,53:881885.
[23] Li,Jiayu,ZengZhong,QiaoLong,2019,“AppliedMathematicsandMechanics”,40(9):957-967.
[24] Li D , Qiu X ,Yu L,Zheng Z,Ma P , Qi F,2014 , “Experiment and numerical simulation of droplet impacting onto a wetted surface”, Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery,45(12):9-17.
[25] Liang Gangtao, Guo Yali, Shen Shengqiang,2012, “Analysis on the formation mechanism of jet and spray of droplet impinging on liquid film”.
[26] Guo jiahong ,Dai shiqiang.2008, “Experimental study on the process of droplet impingement liquid film”.

[27] Zhang Bin,Zhong Junwei,Zhai Yaxin,Guo Penghua,2018,"Experimental and Experimental and Numerical Study on Droplet Collision Force with Wall".

[28] Zhang Bin, Han Qiang,Yuan Xiaofang,LIJingyi,2013, "Simulation of impact force of drop impacting on Horizontal plate".