IMPACT OF RABBIT BLOOD DROP ON
A SUPER-HYDROPHOBIC SURFACE

A Thesis Presented

By

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ABSTRACT

The blood drop impact behavior was found to have an unusual stability related to the blood thixotropy and deformability of individual red blood cells.

Investigation on drop impact on a super-hydrophobic surface was conducted for impact Weber number in the range of $10 < We_{imp} < 400$. The experiment adopted healthy and expired blood (90% less red blood cells compared to healthy blood) samples, aiming to verify the role of red blood cells in impact behavior. Images and video records were analyzed. Contrasting expired blood, healthy blood showed unique stability in fingering and jetting.

**Keywords:** Blood, Red Blood Cells, Non-Newtonian, Drop Impact, Super-hydrophobic, Spreading, Finger, Jetting, Breakup.
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1. Introduction

1.1 Motivation

The primary objective of this research is to connect the deformation of red blood cells (RBC) and thixotropy or blood shear thinning property, which affects the stability of blood impact dynamics. Once this relation is established, it will serve as a step forward in developing a cost-effective blood diseases diagnostic technique. This study is based on the assumption that the decrease of RBC can be revealed by comparing the drop impact between healthy blood and expired blood. Impact dynamics is related to the properties of fluid (density, surface tension, viscosity, shear modulus, etc.).

A control experiment was designed and conducted. We adopted expired blood (RBC count drops by 90% from the healthy counterpart) to simulate diseased blood upon impact in terms of spreading, fingering and jetting. Previous research mainly focused on healthy rabbit blood impact for impact Weber number in the range of $20 < We_{imp} < 180$. The present work extended to $10 < We_{imp} < 400$, and compared samples with normal and reduced RBC density to investigate the influence of cell counts. The convenient experimental setup and techniques will have potentials in disease diagnosis.

1.2 Background

When a liquid drop strikes a solid surface, the drop impact process starts. This instantaneous, microscopic, also ubiquitous phenomenon has been investigated for nearly a century. The underlying mechanism attracted numerous scholars for it is a key
element of a wide variety of phenomena encountered in technical applications, such as ink-jet printing, rapid spray cooling of hot surfaces (turbine blades, rolls in rolling mills for steel production, lasers, semiconductor chips, and electronic devices), annealing, quenching of aluminum alloys and steel, fire suppression by sprinkles, internal combustion engines, etc. (A.L. Yarin 2006).

Research in drop impact on a solid surface mainly focuses on sequential phenomenon of: spreading, splash, rebound, fingering, jetting, etc. and the dynamics of impact. Yarin discussed more detailed experimental and theoretical investigations of droplet impact on thin liquid layers and dry solid surfaces (Yarin 2006). In Rein’s review, droplet impact is released to impacted surface, impact velocity, and droplet geometry, though most of the theoretical considerations were based on the assumption of spherical drops (Rein 1993). Huang et al. (X. Huang, 2019) compared pure water, 15 wt.% cornstarch colloidal solution, whole milk and healthy rabbit whole blood drops impact on super-hydrophobic surfaces, and blood anomaly, which leads to smaller spreading ratio $\beta$ (defined as the ratio of the maximum contact diameter to the droplet diameter prior to impact), minimal coronal finger numbers and coronal splash, and a more stable jet upon rebound. Such behavior is governed by blood thixotropy, a direct consequence of RBCs and their changing geometry as shown in Fig. 1.1.
1.2.1 Spreading Dynamics

A number of theoretical models are available in the literature in spreading characteristics. Clanet et al. investigated the liquid drop of low viscosity impact on a super-hydrophobic surface and found the maximal spreading diameter to be a function of $D_0 We^{1/4}$, where $D_0$ is the original diameter prior to impact (Clanet, Beguin, Richard and Quere 2004). In the literature there are two ways to predict the spreading diameters: momentum or energy conservation equations. Wildeman et al., based on the energy conservation, studied drop impact on a free-slip surface and no-slip surface using a numerical approach. They put forward a generalized rule of energy loss for droplets that exercise large deformation during impact. The governing equation applied to droplets in general, and was used to predict the spreading parameters in free-slip surface. The model was further extended to spreading on the no-slip surface (S. Wildeman, C. W. Visser, C. Sun and D. Lohse 2016). Wildeman’s numerical results were supported by Smith’s measurement in blood droplets. Smith et al. studied blood droplet impact on surfaces with various roughness and wettability at different velocities. Their finding
was consistent with Wildeman’s model and showed surface properties playing only a minor role in droplet spreading (F. R. Smith, N.C. Buntsma and D. Brutin 2018).

1.2.2 Fingering and Splash

Fingering refers to peripheral spires at the final stage of spreading. At high impact velocity or high $We_{imp}$, fragmentation into daughter droplets might occur known as splash. Fingering and splash are closely related (Huang 2019). A central film with uniform thickness expands radially outwards bounded by a toroidal rim (Schroll 2010). Roisman et al. investigated fingering and splash of drop impact onto a solid surface and liquid surface. They attributed the mechanism to the bending instability of a droplet rim (I. V. Roisman, K. Horvat, and C. Tropea 2006). Huang’s study on water droplet impact established a transverse rim instability model developed from the Plateau-Rayleigh (P-R) instability criterion to predict the number of fingers and was supported by their experimentally verified (Huang 2018).

Non-Newtonian fluids such as blood have been extensively investigated. Hulse-Smith et al. conducted an experimental study to determine the diameter and velocity of blood drops through measuring the size of bloodstains (contact diameter, number of fingers, etc.) falling on various surfaces, and found the bloodstain diameters and finger numbers to increase with both the impact velocity and the original diameter of the blood drops (L. Hulse-Smith, N. Z. Mehdizadeh, and S. Chandra 2005).

1.2.3 Jetting

Jetting is the last stage in the time sequence of drop impact. Jetting (also known
as Worthington Jet) was first reported by Worthington (Worthington 1908) to account for droplet recoiling after spreading under the influence of surface tension. When a drop hits on a dry solid surface, jetting only occurs when recoil takes place without splashing (X. Huang 2019). Under specific conditions, the tip breaks away from the main jet and generates secondary droplets, as governed by the Rayleigh-Plateau instability (S. Gekle and J. M. Gordillo 2010). In contrary, Huang investigated healthy rabbit whole drops impact on a super-hydrophobic surface. The fact that the impact droplet remained intact without fragmentation during jetting was due to the underlying stability of blood caused by an internal flow from the main jet towards the tip.

Inspired by these former studies, a set of control experiments were conducted in the present work on impact of healthy and expired rabbit whole blood drops on a super-hydrophobic surface is conducted. Analysis of image using Matlab based on a computational model was performed.
2. Theory

2.1 Definition

A few essential jargons and non-dimensional parameters are defined in this section.

2.1.1 Original Diameter, Contact Diameter and Spreading Factor

Fig. 2.1 shows the spreading process. A few geometric variables are defined as follows.

(a) $D_o$ is the diameter of a droplet released from the pipette before it contacts the super-hydrophobic surface.

(b) $D_c$ is the diameter of the circular contact interface with the substrate.

(c) $D_{c,max}$ is the maximum contact diameter as the droplet spreads on the substrate.

These diameters were captured by a high-speed camera and measured from digital videos using Matlab.

![Figure 2.1: Spreading process from one trial ($We_{imp}$=25.9).](image)
A dimensionless spreading factor is defined as:

\[ \beta = \frac{D_c}{D_o} \]

with a maximum value of:

\[ \beta_{max} = \frac{D_{c,\text{max}}}{D_o} \]

### 2.1.2 Velocity and Weber Number

Another set of dynamic variables is defined as:

(a) \( v_{\text{imp}} \) is impact velocity:

\[ v_{\text{imp}} = \frac{\Delta L}{\Delta t} \]

Where \( \Delta L \) is the infinitesimal vertical displacement of the center of mass in droplet from one frame (0.167ms) prior to impact on the substrate to the moment that the droplet comes into direct contact with the substrate, and \( \Delta t \) is the time elapse. The jet velocity is determined by converting the number of frames obtained by the high-speed camera.

Since it is difficult to determine exact location of center of mass, an indirect method is used to measure \( \Delta L \) by assuming a spherical geometry:

\[ \Delta L = \frac{H_1 + H_2 - H_3}{2} \]

where \( H_1, H_2 \) and \( H_3 \) are elevations from three different points of droplet to the substrate as shown in Fig. 2.2.
Figure 2.2: Measurement of $\Delta L$

(b) Jet velocity: $v_{\text{jet}}$: 

$$v_{\text{jet}} = \frac{\Delta X}{t}$$

In this equation, $\Delta X$ represents the displacement of the jet at the very beginning of the jetting process, as indicated in Fig. 2.3. $\Delta t$ is time in seconds it requires. Both of $\Delta L$ and $\Delta X$ were obtained from videos recorded by the high-speed camera.

Figure 2.3: Measurement of $\Delta X$

(c) The impact weber number is given by:

$$We_{\text{imp}} = \frac{\rho v_{\text{imp}}^2 D_0}{\sigma}$$
where $\rho$ and $\sigma$ are the blood droplet density and surface tension, respectively.

(d) The jet weber number is given by:

$$We_{jet} = \frac{\rho v_{jet}^2 D_{c,max}}{\sigma}$$

### 2.1.3 Stages

There are four consecutive stages of droplet impact defined by the time varying $\beta$.

At the first contact with the substrate ($0 < \beta \leq 1$), the drop by and large retained its spherical geometry but deformed slightly into a cap as shown in Fig.2.4 (a). A spreading stage followed ($1 < \beta \leq \beta_{max}$) as contact area continued to expand while the central bulge further melted as shown in Fig.2.4(b). The radial velocity parallel to the substrate increases at the expense of the vertical downward momentum. The presence of surface tension and the associated increase in surface energy restrained the lateral expansion of the droplet. As radial velocity diminished and eventually vanished, the contact area reached a maximum.

As a result, the surface area of the droplet decreases rapidly after the contact diameter achieves its maximum extent. At this point, the recoiling stage is triggered. As shown in Fig.2.4(c), the recoiling stage continues as the contact diameter reduces to the original diameter, which can be described as: $1 < \beta \leq \beta_{max}$. With the further decrease of the contact diameter, more liquid flows upward and forms jetting under the control of surface tension, and this growth may cause the entire drop to rebound at the end of this jetting stage ($0 < \beta \leq 1$) as indicated in Fig.2.4(d). The complete process of drop impact on super-hydrophobic surface including these four stages has been demonstrated as a function of time in Fig. 2.5.
Figure 2.4: Blood drop impact at the initial stage (a), spreading stage (b), recoiling stage (c) and jetting stage (d).

Figure 2.5: Four stages of the drop impact process. From Dynamics of Newtonian and Non-Newtonian Liquid Droplet Impact on Super-Hydrophobic Solid Surfaces, by Xiao Huang, June 2019, Copyright (2019) by Xiao Huang
3. Experiments

This part includes experimental apparatus and its components for this study, a complete experimental process involves preparation of the super-hydrophobic surface, measurement of surface tension and density, and step-by-step experimental procedures will also be discussed in this section.

3.1 Experimental Apparatus

The assembled homemade experimental apparatus shown in Fig. 3.1, they are composed of 5 components that are given below.

Figure 3.1: Experimental apparatus from front-view and side-view
3.1.1 High-Speed Camera

Edgertronic™ is a high-speed monochrome camera used in this study, which has a web-browser based control panel with live preview. It also has a range of exposure from 1/10 to 1/250,000 seconds, a settable resolution from 1280x1024 to 192x96, an ISO range of 6400 to 102400, and a maximum frame rate up to 17,791 fps (base on the resolution: 192x96).

Figure 3.2: High-speed Camera

3.1.2 Optical Lens

The Tokina AT-X 100mm f/2.8 - AT-X M100 PRO D macro lens is optimized for use with the high-speed digital camera in this experiment. This macro lens capable of life-sized (1:1) reproduction at 11.8” (30cm), and its multi-coating matches the highly reflective silicon based CCD and CMOS sensors in the digital camera.
3.1.3 Light Source

An RPS Studio CooLED 100W studio light used in experiment serving as a light resource. The RPS Studio CooLED 100W studio light is equivalent to 1000W with a reflector attached around its 100 watts bulb. The lighting intensity is adjustable for three levels via brightness setting button on the back.
3.1.4 Pipette

Rainin Classic Pipette PR-200 is a manual single-channel pipette, the range of its volume is 20μL - 200μL with 0.2μL manual increment. The accuracy and precision of the pipette is ±2.5% / 0.5μL and 1% / 0.2μL separately.

![Rainin Classic Pipette PR-200](image)

Figure 3.5: Rainin Classic Pipette PR-200

3.1.5 Aluminum Frame

As shown in Fig. 3.1, a pipette is hung from a vertical-adjustable metal frame. The super-hydrophobic surface is held by the frame exactly under this pipette. So that droplet is released from the pipette to the super-hydrophobic surface within a desirable range of elevation. The tests in this study were run for a range of elevation (which is the distance from the tip of the pipette to the super-hydrophobic surface) from 12.7mm (0.5inch) to 215.9 mm (8.5inches) with 12.7mm (0.5inch) intervals.

3.2 Preparation of Super-hydrophobic Surface

In this research, all experiments are conducted on a super-hydrophobic surface, for it allows the droplet impact behaviors to be observed most clearly.
Simple fabrication of a super-hydrophobic surface using a copper plate as a substrate is used in this study. First off, the copper plate is cut into 2x5 cm pieces. Each piece was then polished on one side to remove the oxide layer or any other chemical deposits. The polished copper plate is placed into the prepared 0.01 M AgNO$_3$ (aq) for 2 minutes. The nano-textured silver is deposited on the copper plate in this step. After that, the coated copper plate is rinsed by de-ionized (DI) water for 20 seconds and blown dried to be ready for dipping in a 1 mM heptadecafluoro-1-decanethiol (HDFT) solution. After 5 minutes, a self-assembled monolayer with non-polar molecular segments is formed on the coated copper in the HDFT solution, and the plate is put in dichloromethane for 20 seconds to remove the remains of HDFT solution.

The static contact angle is measured using a high-speed camera to record static DI water droplets on the prepared super-hydrophobic surface and then applied a Matlab program to measure the static contact angle from the recorded video, which leads to being $150 \pm 1^\circ$ which can be illustrated in the Fig. 3.7.
3.3 Surface Tension Measurement

The pendant drop selected plane method is adopted to measure the surface tension of blood. A snapshot of blood droplet suspended from the tip of the pipette is taken to be evaluated the largest diameter $d_e$ as illustrated in Fig. 3.4, then diameter $d_s$ of the plane which is at a distance $d_e$ from the bottom of the droplet is measured, so the surface tension of this droplet is given by:

$$\sigma = \frac{\Delta \rho gd_e^2}{H}$$

Where $\Delta \rho$ is the density difference between blood droplet and air at room temperature (20°C) and atmosphere pressure (101kpa), $H$ is determined from the tables in Appendix at the end of this thesis, according to the value of $S$, which is the ratio of $d_s$ and $d_e$. 

Figure 3.7: DI water droplet on a super-hydrophobic surface captured by high-speed camera (left) and static contact angle measurement in Matlab (right)
Figure 3.8: A snapshot of blood droplet suspended from the tip of the pipette

3.4 Density Measurement

The volume of the blood sample is measured by the pipette, and its mass is measured with an analytical balance with a capacity range of 10mg to 120g and a readability of 0.1mg. There are six groups of blood samples whose volumes and masses were measured at room temperature (20°C) and atmospheric pressure (101kpa) and densities were calculated. The final result of blood density is taken from the average of each group.

3.5 Experimental Procedures

Experimental procedures will be introduced in two parts: experiments in which the droplet was viewed from the side and experiments in which the droplet was viewed from the top will be discussed in this section. The side-view experiments are designed to investigate the spreading and jetting behaviors. However, the top-view experiments are devised for the purpose of studying fingering behaviors of blood droplets.
3.5.1 Experimental Procedures for Side-Views

The pipette absorbing 160mL of blood is adjusted initially at an elevation of 12.7mm (0.5inch) away from the super-hydrophobic surface held by the vertical-adjustable metal frame.

As seen in Fig. 3.1, the high-speed camera is placed horizontally with respect to the super-hydrophobic surface, then the camera in a lower sensitivity is tested and settled by adjusting the tripod to a proper height and angle to make sure the super-hydrophobic surface was in the center of the screen. Once the surface is in the center, the camera could be set to a sensitivity of 12000 ISO, a shutter of 1/6500 seconds and a frame rate of 6000 per second as shown in Table 3.1. Since the sensitivity of the high-speed camera has been changed, the LED light is provided as a light supplement to make sure the details of the super-hydrophobic surface can be recorded by the high-speed camera.

<table>
<thead>
<tr>
<th>Settings</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>12000 ISO</td>
</tr>
<tr>
<td>Shutter</td>
<td>1/6500 seconds</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>6000.000 per second</td>
</tr>
<tr>
<td>Duration</td>
<td>0.700 seconds</td>
</tr>
<tr>
<td>Pre-trigger</td>
<td>50 %</td>
</tr>
<tr>
<td>Shot Count</td>
<td>1 shots</td>
</tr>
</tbody>
</table>

Table 3.1: The settings of high-speed camera
When the blood droplet is released from the pipette and entered the screen of the high-speed camera, the process of this droplet impact was recorded by the computer-controlled camera, which is operated by pressing a trigger on the computer.

The same procedure is repeated 5 times in this initial elevation (12.7mm) to warrant reproducibility. The vertical-adjustable metal frame is lifted to change to the next elevation (25.4mm) to continue the experiments above. This repeated process continues until the pipette rose up to its highest elevation, which is 215.9 mm (8.5 inches).

3.5.2 Experimental Procedures for Top-View

The procedure of top-view experiments is similar to the side-view experiments, except for the position of the high-speed camera and light sources. The high-speed camera is held by tripod on the experimental desk, at an angle from the centerline of the camera to the horizontal line is about 45°, which is evident in Fig. 3.9. Also, the horizontal distance between high-speed camera and the super-hydrophobic surface is much closer than in the side-view experiments. Since the LED light cannot be projected into the lens of high-speed camera directly, which is different from experiments of a side-view, one more LED light is required to keep the view in high-speed camera bright enough and to avoid unnecessary light reflections.
The experiments of top view are also conducted in a range of elevation from 12.7 mm (0.5 inches) to 215.9 mm (8.5 inches) up to 11 groups of heights with 3 repeats in each group.

### 3.6 Image Analysis

In the post-processing of experiments, the conversion ratio between the real length and the pixels in the test videos has to be obtained first. Then a Matlab-based image processing program (as shown in Fig. 3.10) is applied to measure required data referred in chapter 2 from the test videos. The procedure is summarized as follows:
**Step 1:** Set a caliper at a known length, then put it at the exact same place where the drop impact the super-hydrophobic surface, keep its front perpendicular to the high-speed camera.

**Step 2:** Use the high-speed camera to capture static videos of the caliper.

**Step 3:** Convert the videos into pictures and calculate the conversion scale between real length and pixels in the test videos. Repeat step 1~3 for 5 times to ensure repeatability.

**Step 4:** Convert every frame of the videos recorded in the experiments into pictures.

**Step 5:** Select pictures needed to be analyzed, then set parameters in the Matlab program to measure the needed data.

![Interface of Matlab-based image processing program](image.png)

**Figure 3.10:** Interface of Matlab-based image processing program
4. Results and Analysis

In this section, the result of experimental investigation on several general impact behaviors of blood drop impact on a super-hydrophobic surface is revealed. Also, the blood drop including healthy rabbit whole blood drop and expired rabbit blood drop (the red blood cells are 90% less than healthy blood), would be discussed together to compare their different impact behaviors due to the influence of red blood cells.

4.1 Healthy Blood and Expired Blood

This study concerns the red blood cells as a key role for the different impact behaviors between healthy blood and expired blood. For this purpose, a microscope is operated to get the images of red cells in both healthy blood and expired blood aims to compare the quantity and shape of red cells visually.

The healthy rabbit blood was bought from Innovative Research Inc., and was stored at 2-8°C. We use expired blood, whose red blood cells is about 90% less than the healthy blood that can be observed in Fig.4.1 as a simulation to the diseased blood.

![Figure 4.1: Red blood cells in healthy blood (left), and expired blood (right)](image-url)
As illustrated in Fig. 4.1, the expired blood sample has much less amount of red blood cells compared with the healthy blood sample. Besides, the red cells in expired blood samples tend to twist, shrink to a smaller size and change their regular shapes. All these features suggest that most of the red cells in expired blood have broken. Therefore, how red blood cells affect the blood drop impact behaviors can be detected by comparing the droplet impact experimental results of healthy blood and expired blood.

4.2 Droplet Impact Behavior

Droplet impact behaviors in this experimental investigation as mentioned above have four parts: spreading, splashing, fingerling and jetting, among them. Spreading, fingerling and jetting parts will be discussed separately in the following sections. The splashing will be combined and explained within these three parts.

4.2.1 Spreading

The spreading process happens in the spreading stage, which has been indicated in section 2.1.3, and during this process, the droplet constantly expands to its maximum extent. The maximum extent is determined by the initial conditions including impact Weber number $W_{\text{imp}}$, impact Reynolds number $R_{\text{imp}}$, etc. Our research on spreading part concentrates on studying the maximum spreading factor: $\beta_{\text{max}}$ as a function of impact Weber number: $W_{\text{imp}}$. We conducted horizontal view experiments for Weber number in the range of 10–400. Fig. 4.2 is a summary of our horizontal view experiments, it compares the maximum spreading of blood droplets at different $W_{\text{imp}}$. 
Figure 4.2: Healthy and expired blood drop impact at maximum spreading for different impact Weber numbers in horizontal view

Generally, both healthy and expired blood droplets spread with a smooth rim without spires for $W_{e_{imp}}=10\text{–}100$, as shown in Fig. 4.2. However, when the $W_{e_{imp}}$ increases, in the same $W_{e_{imp}}$ group, the expired blood generates more perturbations at their rims than healthy blood. Since the $\beta_{max}$ cannot be compared from tests video directly, we measured $D_c$ and $D_o$ using Matlab as mentioned in section 2.1.1 to obtain $\beta_{max}$, then plotted $\log\beta_{max} (\log W_{e_{imp}})$ for comparing the two blood samples (as shown in Fig. 4.3).

In former studies, spreading of water, milk, cornstarch solutions and healthy rabbit blood drop impact has been discussed for impact weber number in the range of $20 < W_{e_{imp}} < 180$, and blood droplet is believed to have a special feature of spreading
unlike the other liquids with linear $\beta$ in log-log graph, blood shows bilinearity with $k = \frac{d \beta}{d We_{imp}} \approx 0.235$ when $We_{imp} < We_{imp}^* = 105$ and $k \approx 0.442$ otherwise (X. Huang, Wan, and Taslim 2018). The $We_{imp}^*$ is a threshold corresponds to a shear rate of $\dot{\gamma} \approx 800 \text{s}^{-1}$, which is roughly the threshold when rouleaux of red blood cells begin to break apart into individual discocytes (X. Huang, Wan, and Taslim 2018).

Our experiments, however, expanded the impact weber number to the range of $16 < We_{imp} < 400$ for both healthy blood and expired blood, then two thresholds instead of one are found in the healthy blood experiments: One is when $We_{imp1}^* = 30$, another is when $We_{imp2}^* = 200$. Fig. 4.3 shows the degree of spreading: $\log \beta$ ($\log We_{imp}$) concluded from our experimental results, there are two transition points in this graph at $\log We_{imp1}^* = 1.5$ ($We_{imp1}^* = 30$) and at $\log We_{imp2}^* = 2.3$ ($We_{imp2}^* = 200$) respectively.

When $\log We_{imp} < 1.5$ ($We_{imp}^* < 30$), the increasing tendency of spreading ratio is much smoother than it in the range: $1.5 < \log We_{imp} < 2.3$ ($30 < We_{imp} < 200$), nevertheless, when $2.3 < \log We_{imp}$ ($200 < We_{imp}^*$), the change of spreading ratio is back to become smaller again.
Figure 4.3: Comparison of $\log \beta_{\text{max}}$ ($\log We_{\text{imp}}$) between healthy blood and diseased blood

The first transition point, when $\log We_{\text{imp}}^* = 1.5$ ($We_{\text{imp}}^* = 30$), is believed to be related to the influence of droplet deformation (S. Wilderman, C. Visser, C. Sun and D. Lohse 2016). Wilderman et al.’s study used direct numerical simulations to predict the spreading factors of drop impacting on both free-slip (neglecting surface friction) and no-slip (surface friction present) surfaces for $We_{\text{imp}}$ from 0.3 to even larger than 3000. Wilderman et al. employed two deformation modes based on different range of impact weber numbers: the impacting drop has a puddle shape (as evidenced in the Fig. 4.3) when $We_{\text{imp}} < 30$; for $We_{\text{imp}}$ larger than 30, it starts to transform into a pizza shape mode (indicated in Fig. 4.4), this pizza shape continues to be more intensively for $30 < We_{\text{imp}} < 3000$ and there is no more transformation of shape according to their study. Wilderman et al. defined the drop impact in the range of $We_{\text{imp}} < 30$ as elastic impact, where the drop experiences a small-scale deformation, and in this regime, the initial kinetic energy is converted into the work done against the surface tension. However,
the impact in the region of $30 < W_{\text{e_{imp}}} < 3000$ was defined as an inelastic regime, where the deformation of droplet changes into another mode, and the initial kinetic energy is dissipated associated with surface deformations which leads to the spreading factor increases more intensive with weber number compared with that in the elastic area. Wilderman et al. also underscored that this total energy loss is due to a universal head loss that is independent of the properties of the liquid, which means it can be applied to any liquid droplet cases.

Figure 4.4: Wilderman et al.’s numerical simulations of spreading ratios as a function of the impact Weber number. Green symbols are used for impacts on a free-slip surface, and red symbols for impacts on a no-slip surface. The insets show the typical shape of the droplets at low (puddle shaped), and high Weber numbers (pizza shaped). From On The Spreading of Impacting Drops, by Sander Wildeman, Claas Willem Visser, Chao Sun and Detlef Lohse. Journal of Fluid Mechanics, Volume 805, October 25, 2016, pp. 636-655. Copyright (2016) by Cambridge University Press.
Wilderman et al.’s study serves as a compelling explanation for our research, which also considers \( \text{We}_{\text{imp}}^* = 30 \) a critical point, in the meantime, the result of our work fulfills their study by serving as an experimental confirmation.

Moreover, along with the increase of \( \text{We}_{\text{imp}} \), the spreading factor \( \beta \) related to surface area continues to grow till gets to its limit as shown in our result. There exits another critical point when \( \text{We}_{\text{imp}}^2 = 200 \) approximately, when \( \text{We}_{\text{imp}} > 200 \) the change of spreading ratio \( \beta \) starts to become moderate as shown in Fig. 4.4.

The result of expired blood experiments agree with the healthy blood experiments in a great extent, and it also shows a significant change of spreading factor when \( \log \text{We}_{\text{imp}}^1 = 1.5 \) (\( \text{We}_{\text{imp}}^1 = 30 \)) as illustrated in Fig. 4.4. However, at \( \log \text{We}_{\text{imp}}^2 = 2.5 \) (\( \text{We}_{\text{imp}}^2 = 316.2 \)) where a second critical point in healthy blood experiments exists. The expired blood has already started to splash on account of its instability compared with healthy blood (see Fig. 4.2, \( \text{We}_{\text{imp}} = 300\sim400 \)). For this reason, whether there also exists a second transition point in diseased blood cannot be confirmed. The instability, an important difference between healthy blood and expired blood, and will be mainly discussed in the later jetting chapter.

### 4.2.2 Fingering

As described previously in section 2.1.3, from the spreading stage (\( 1 < \beta \leq \beta_{\text{max}} \)) to the recoiling stage (\( 1 < \beta \leq \beta_{\text{max}} \)), the kinetic energy caused by gravitational potential energy in this period converts into surface energy incessantly until the total surface tension surpasses the kinetic energy then becomes the dominant force to govern the transformation of the droplet. Appropriately, the surface tension between air and liquid
limits the surface area of the droplet, makes it decrease to its minimum value and, as a
consequence, the finger appears around the peripheral of droplet lamella.

The fingering behavior of water has been investigated thoroughly using a
transverse rim instability analysis in Huang et al.’s research, and the governing
equations are formulated which can be used to predict the number of fingers for a given
impact Weber number, and Huang et al.’s new model, as an extension of the classic
Rayleigh-Plateau model, agrees with their experimental results in the range of:
$60 < \text{We} < 160$ (X. Huang, Wan, and Taslim 2018).

Our experimental investigation concentrates on healthy blood droplet and expired
blood droplets. The top-view experiments as mentioned in section 3 are conducted to
investigate the blood fingering behaviors. The experiments for studying fingering
behaviors have been conducted in a range of elevation from 12.7mm (0.5 inches) to
215.9 mm (8.5 inches) up to 11 groups of heights with 3 repeats in each group for both
healthy blood and diseased blood droplet to warrant reproducibility.

In our research, the finger numbers were counted at the droplet extended to its
maximum spreading. Fig. 4.5 is a snapshot from one of our top view experiments,
axisymmetric assumption was applied in fingers measured. For example, by assuming
the fingers distribute around central axis evenly, we can count the number of fingers
from one side of the droplet, which is 10 in Fig 4.5, then multiplied by 2, minus 2, and
finally the number of fingers is 18.
Being different from the side-view experiments which are exploited in spreading and jetting parts, the top-view experiments require the high-speed camera to be held by tripod on the experimental desk at an angle that is almost perpendicular to the super-hydrophobic surface. As a result, the impact velocity: $v_{\text{imp}}$ cannot be obtained from the top-view experiments, because calculating impact velocity requires the displacement difference $\Delta L$ of droplet from one frame prior to its impact to the moment that the droplet impacts the super-hydrophobic surface, and that, has to be captured by the high-speed camera in a horizontal view to the super-hydrophobic surface. Furthermore, the impact weber number $We_{\text{imp}}$ cannot be calculated either, because of the absence of impact velocity. To solve this problem, we adopted the average of impact velocity obtained from the side-view experiments from the same group as a simulation of the
actual impact velocity and calculate impact weber number based on this simulated impact velocity.

Fig. 4.6 summarizes our experimental results, it compares finger behaviors of healthy and expired blood samples in separate Weber ranges.

![Healthy Blood](image)

**Healthy Blood**

- $We_{imp}=80-100$
- $We_{imp}=100-120$
- $We_{imp}=120-140$
- $We_{imp}=140-160$

![Expired Blood](image)

**Expired Blood**

- $We_{imp}=80-100$
- $We_{imp}=100-120$
- $We_{imp}=120-140$
- $We_{imp}=140-160$

Figure 4.6: Healthy and expired blood droplet impact top view at their maximum spreading.
Then we plot the number of fingers against the impact weber number in Fig. 4.7. It is easy to conclude that the finger numbers and $We_{imp}$ of healthy blood and expired blood have a linear relation in the figure, the number of fingers increases as a response to the rising of $We_{imp}$. However, the healthy blood droplets start to form fingers at approximately $We_{imp} = 130$. The minimum $We_{imp}$ for fingers generation in expired blood droplets is at $We_{imp} = 110$. Moreover, the expired blood drops have more fingers than healthy blood when they are both in the same group of impact Weber numbers.

Through comparing the fingers formation in healthy and expired blood, a negative correlation of RBC and finger number is confirmed, which means the reducing RBC leads to a less coronal fingers.
4.2.3 Jetting

As mentioned in Section 2, at the final stage of impact, the droplet keeps recoiling and the contact diameter decreases consistently. With the further decreasing of contact diameter, more liquid flows upward and forms jetting under the control of surface tension, and this growth may cause the entire drop to rebound at the end of this jetting stage ($1<\beta\leqslant0$). This section specializes in this jetting process, applies analysis on the comparison of the different outcomes within both healthy blood and expired blood.

As discussed in the previous sections, instability is an important difference between healthy blood and expired blood and also is the main topic of this thesis. It should be noted that the jet instability is measured by the number of breaks for a single blood droplet. In Section 2, the entire process of healthy blood and expired blood droplet impact on the super-hydrophobic surface has been revealed in Fig. 2.4. This part will mainly represent and compare details of jetting process of healthy and expired blood.

Fig. 4.8–Fig. 4.12 are selected to represent our experimental results, they compare jetting process of healthy and expired blood samples in separate Weber ranges. The differences between these two blood samples are more remarkable in larger $We_{imp}$. As shown in Fig. 4.11, healthy blood droplet remains stable when expired the blood drop experiencing a tip fragmentation. However, in our experiments, both healthy and expired blood jets emanate satellite droplets on their tips (which is known as “breakup”) when rising or falling sometimes. Hence further analysis is needed to compare the different jetting outcomes of healthy and expired blood.
Figure 4.8: Jetting of healthy and expired blood drop impact on a super-hydrophobic surface for $We_{imp}=10$–$30$ in horizontal view
Figure 4.9: Jetting of healthy and expired blood drop impact on a super-hydrophobic surface for $We_{imp}=30\sim100$ in horizontal view
Figure 4.10: Jetting of healthy and expired blood drop impact on a super-hydrophobic surface for $We_{imp}=100$--$200$ in horizontal view
Figure 4.11: Jetting of healthy and expired blood drop impact on a super-hydrophobic surface for $We_{imp}=200\sim 300$ in horizontal view
Figure 4.12: Jetting of healthy and expired blood drop impact on a super-hydrophobic surface for $We_{imp}=300-400$ in horizontal view
Furthermore, we summarized all experimental results and did analysis for them. To begin with, a new jet weber number: $We_{jet}$ is needed to be defined, this jet weber number is different from the impact weber: $We_{imp}$ used in spreading and finger chapters of this research. The $We_{imp}$ used previously involves the $v_{imp}$ and $D_o$ as two of its variables, however, the $We_{jet}$, instead, adopts the maximum contact diameter: $D_{c,max}$ as a characteristic length rather than original diameter $D_o$ used in the impact diameter, this, is for the purpose of reducing disturbance during spreading and recoiling stages. Additionally, since splashing can be observed in several expired blood experiments but not a single splashing case in healthy blood experiments, as is known to all, splashing will reduce the volume of droplets, which will also cause the droplet diameter change. Therefore, $D_{c,max}$ here should be better to be defined as a characteristic length than $D_o$. Also, it is the jet velocity: $v_{jet}$ replacing impact velocity: $v_{imp}$ used in the new jetting weber number. In short, the jet weber number is given as:

$$We_{jet} = \frac{\rho v_{jet}^2 D_{c,max}}{\sigma}$$

The number of breakups versus jet weber number $We_{jet}$ is plotted in Fig. 4.13, in general, for both healthy blood and diseased blood, with the increasing of jet weber number $We_{jet}$, the probability of breakups also increase. Although as shown in Fig. 4.13, it seems that the healthy blood drops break as many as expired blood drops do, yet we cannot conclude that expired blood jet is more stable than healthy blood jet, because the diseased blood droplet starts to splash in a high impact velocity (high impact weber number as well) as discussed in the spreading chapter, and jetting cannot form when this splash happens as mentioned previously. It is splash set upon a limit for the number
of breakups for expired blood jet. As a result, the expired blood jet represents fewer times of breakups compared with the healthy blood jet.

Figure 4.13: Comparison of number of breakups ($W_{\text{jet}}$) between healthy blood and expired blood

Based on the result above, we decided to take a different path to compare the stability of healthy blood drop and expired blood drop. As indicated in Fig. 4.14 and Fig. 4.15, a plot of jet weber number $W_{\text{jet}}$ against impact weber $W_{\text{imp}}$ is adopted for comparing jetting behaviors of healthy blood and expired blood drops. The number of breakups is represented with different color points, then a color map is created to divide several regions based on the numbers of breakups. The only case of healthy blood jet with 3 breakups has been ignored in this color map for it is reasonable to believe this is
an accidentally exceptional case. To sum up, this $W_{\text{jet}} - W_{\text{imp}}$ color map is more suitable to be applied to compare the instability of healthy blood jet and expired blood jet since it includes the impact Weber number: $W_{\text{imp}}$, which plays an essential role in blood jet for the reason given above.

Figure 4.14: $W_{\text{jet}} - W_{\text{imp}}$ color map of healthy blood

Figure 4.15: $W_{\text{jet}} - W_{\text{imp}}$ color map of diseased blood
By comparing the $W_{\text{jet}}-W_{\text{imp}}$ color maps in Fig. 4.14 and Fig. 4.15, one would find the area of blue non-break region shown in expired blood case is approximately 40% of that in the healthy blood case. Moreover, the blue non-break region in healthy blood concentrate in the ranges of impact weber number: $50 < W_{\text{imp}} < 100$ and $300 < W_{\text{imp}}$ mainly while the jet weber number is relatively high: $0 < W_{\text{jet}} < 1800$. In expired blood, however, this blue non-break region is more widespread in the range of impact weber number: $50 < W_{\text{imp}} < 450$ but in a relatively much lower jet weber number: $0 < W_{\text{jet}} < 1000$. In brief, it is obvious that by comparison, the jet of healthy blood is more stable for it maintains non-break status in a relatively high $W_{\text{imp}}$ and $W_{\text{jet}}$. In this light, we can conclude that healthy blood drops have more intensive jet stability than expired blood drops, and this different jetting behavior is from the influence of red blood cells.
5. Conclusion

Experimental studies on both healthy blood and expired blood drop impact on a super-hydrophobic surface are investigated, including several general impact behaviors: Spreading, splash, finger and jetting. Then through comparing the differences between impact behaviors of healthy blood and expired blood, the influence of red blood cells on the instability properties of blood drop impact behaviors is revealed. Therefore, we are able to draw a conclusion that the special stability of healthy blood is caused by the deformation of RBC.
6. Suggestion for Future Work

It is recommended to adopt a more accurate method to calculate the impact weber number used in the study of finger behaviors. It would be better to exploit a second high-speed camera in the top-view experiments to capture snapshots of droplets impact in the horizontal view at the same time, so that a much more accurate impact velocity and impact weber number could be obtained via the implementation of an image analysis based on these snapshots.

Similarly, for acquiring more accurate experimental data, equipment modification to keep the super-hydrophobic surface horizontal during the experiments is needed. Furthermore, an experimental set up that can control the angle of the super-hydrophobic surface would be even better, by which the research topic then can be extended to take the effects of contact angles into consideration. Besides, according to Rein’s review (Rein 1993), the geometric aspects of liquid droplet is also one of the essential factors that would influence the impact outcomes. Most of the theoretical and numerical calculations are based on the assumption that the droplet is spherical (Rein 1993), hence it will be meaningful to calculate the eccentricity of drops (Stow, Hadfield and Cai 1989) at the moment of impact on the super-hydrophobic surface.

For the jetting part, more effective methods to compare the jetting behaviors of healthy blood drop and diseased blood drop especially the different instability properties between these two are needed to be explored in that the influence of red blood cells on jetting will be understood better.

Also, further studies on other non-Newtonian fluids such as cornstarch solutions
in different concentrations, water with solid particles, cooking oil or even other bio-fluids are worth to be explored for investigating the relationship between intrinsic properties of non-Newtonian liquids and shape deformation, internal flow phenomenon as well as energy transfer upon impact process.
# APPENDIX

## Table 1: Parameters for calculating surface tension

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