CHAPTER IV

RESULTS AND DISCUSSION

In order to observe the rebound phenomena in this study, a water droplet with various small sizes was allowed to fall on a highly hydrophobic surface which was a glass plate coated with the plasma-treated polypropylene film. Since the shape of water droplets in air was not perfectly spherical, the center of mass is used to localize the height of water droplets which varied with time. All experimental data are given in Appendix E.

4.1 The Change of Center of Mass

Figure 4.1 and 4.2 show the impact phenomena of water droplet falling on the super-hydrophobic surface. A water droplet volume of 10.9691 mm^3 impacted onto the plasma-treated polypropylene film coated on a glass surface showed 4 rebounds before its energy declined to zero. When a water droplet impacts onto a solid surface, some amount of energy dissipates to the solid surface and surrounding. As a result, the rebounding water droplet has a lower height than the previous rebound. As shown in Table 4.1 the minimum impact height of the droplet increases with increasing number of impact. The greater the impact velocity, the greater the water flow in the radial direction, resulting in lowering the center of mass of water droplets.

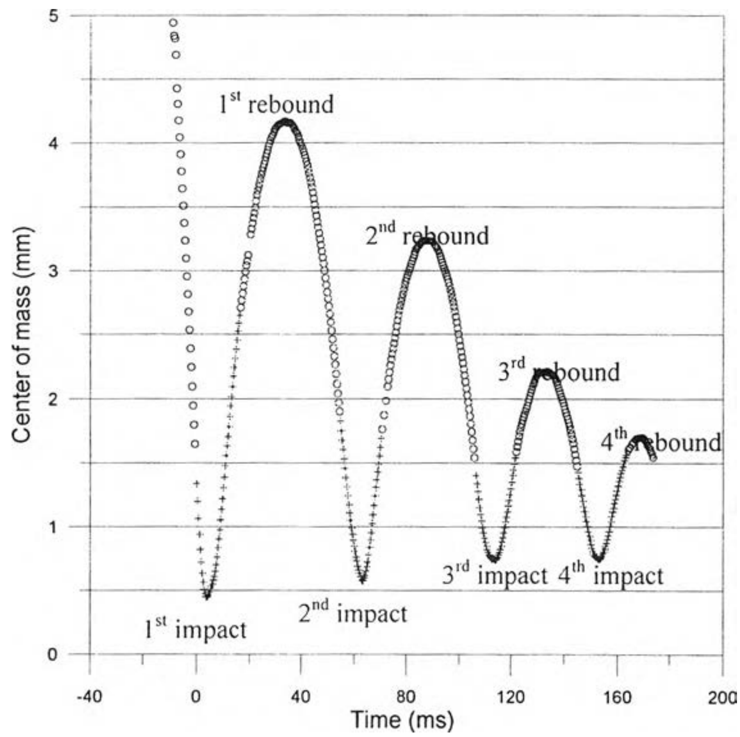


Figure 4.1 The profiles of center of mass of water droplet having size 10.9691mm^3 with an initial impact velocity of 0.4362 m/s onto CF_4 plasma-treated polypropylene film coated on a glass during (o) rebound phase (+) impact phase

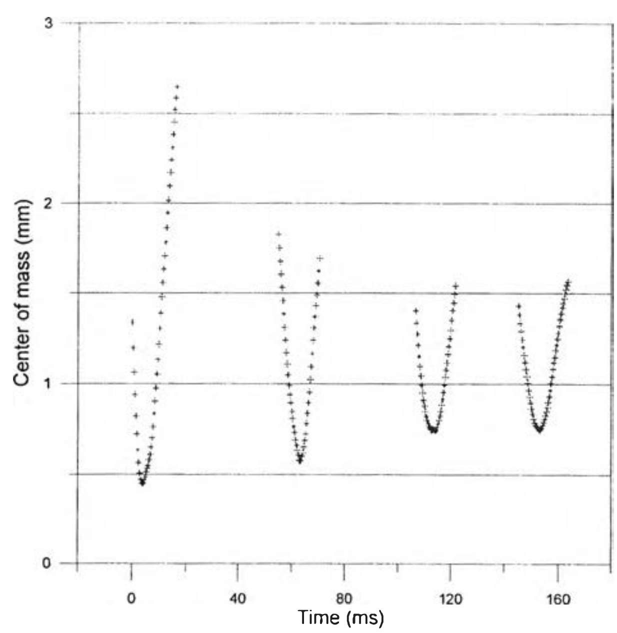


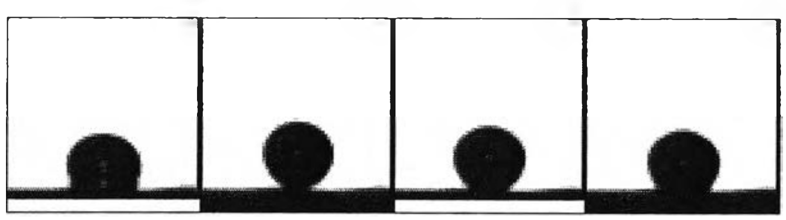
Figure 4.2 The profiles of center of mass of water droplet having size 10.9691mm^3 with initial impact velocity 0.4362 m/s onto CF_4 plasma-treated polypropylene film coated on a glass during (+) impact phase

Table 4.1 Impact velocity and minimum impact height of water droplet having size of 10.9691 mm^3 with an initial impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface.

	Impact Velocity (m/s)	**Minimum rebound height (mm)**
1^{st}	0.2088	0.4477
2^{nd}	0.1981	0.5757
3^{rd}	0.1331	0.7391
4^{th}	0.0629	0.7450

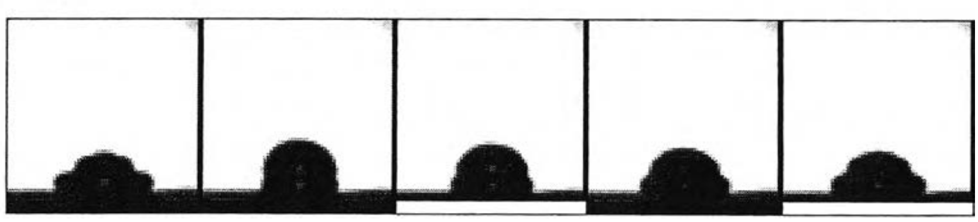
As shown in Figure 4.3, when a water droplet firstly contacts the solid surface it has spherical shape. After that the droplet started to deform and spread into outward horizontal direction. The liquid flow direction changes from vertical to horizontal direction. When it reached the maximum spreading it started to recoil the flow direction change from outward to inward back to the center. Finally, the flow direction changed from horizontal to the upper ward and then detached the solid surface.

Contacting



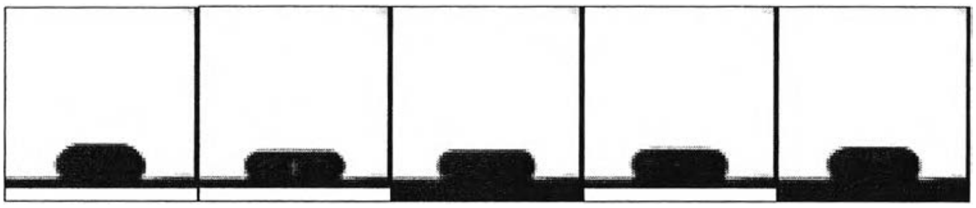
0.00 ms 0.34 ms 0.69 ms 1.03 ms

Spreading



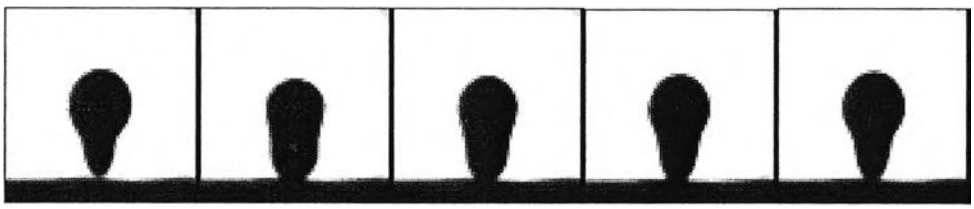
1.38ms 1.72 ms 2.07 ms 2.41 ms 2.76 ms

Recoiling



5.17 ms 5.52 ms 5.86 ms 6.21 ms 6.55 ms

Detaching



13.45 ms 14.14 ms 14.83 ms 15.52 ms 16.21 ms

Figure 4.3 Movement of water droplet during contacting, spreading, recoiling, and detaching

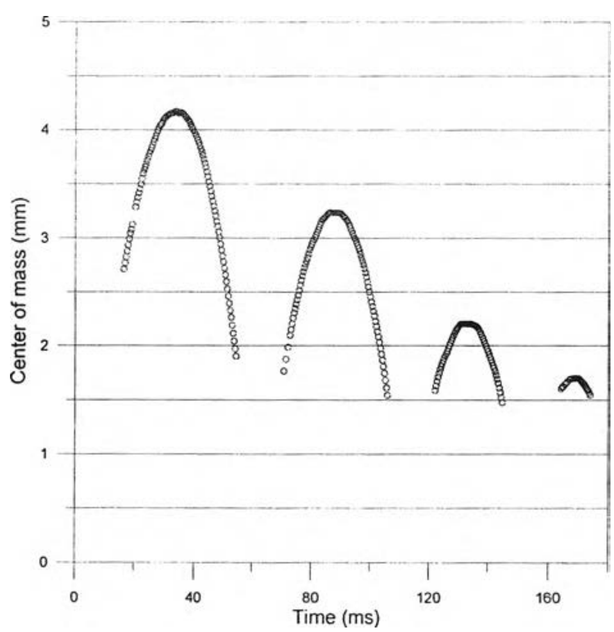


Figure 4.4 The profiles of center of mass of water droplet having size 10.9691mm^3 with initial impact velocity 0.4362 m/s onto CF_4 plasma-treated polypropylene film coated on a glass during (o) rebound phase

Not only the observation during the impact phase but also during the rebound phase. There are several phenomena occurred in this phase such as internal oscillation of rebounding droplet, the change of 2D-volume with projection area, the observation of peaks of maxima and the movement of center of mass both in vertical and horizontal direction. Figure 4.4 shows the change of the maximum height of each rebound. The maximum height of the rebound droplet decreased with increasing number of rebound.

4.2 Internal Oscillation of Rebounding Droplet

The internal oscillation of rebounding droplet results from the internal liquid movement. Figure 4.5, shows the internal liquid movement of the rebounding water droplet stretched both in vertical and horizontal direction sequentially under the studied conditions, the impact energy of the water droplet was not high enough to overcome the surface energy. As a result, the water droplet did not splash after impact. The period of the internal oscillation is not as smooth as in the solid body due to the internal liquid movement. As shown in Figure 4.6, the change of radius in the x and y direction were observed. The oscillation or elasticity in the vertical direction was greater than the oscillation in the horizontal direction because the rebounding water droplet is affected by the gravitational force in the vertical direction

For the 1st rebound, the water droplet had the greatest amplitude (or greater radius) and the longest period of oscillation and for the 2nd rebound, both amplitude and period of oscillation decreased because of the energy loss by the air friction and the contact solid surface.

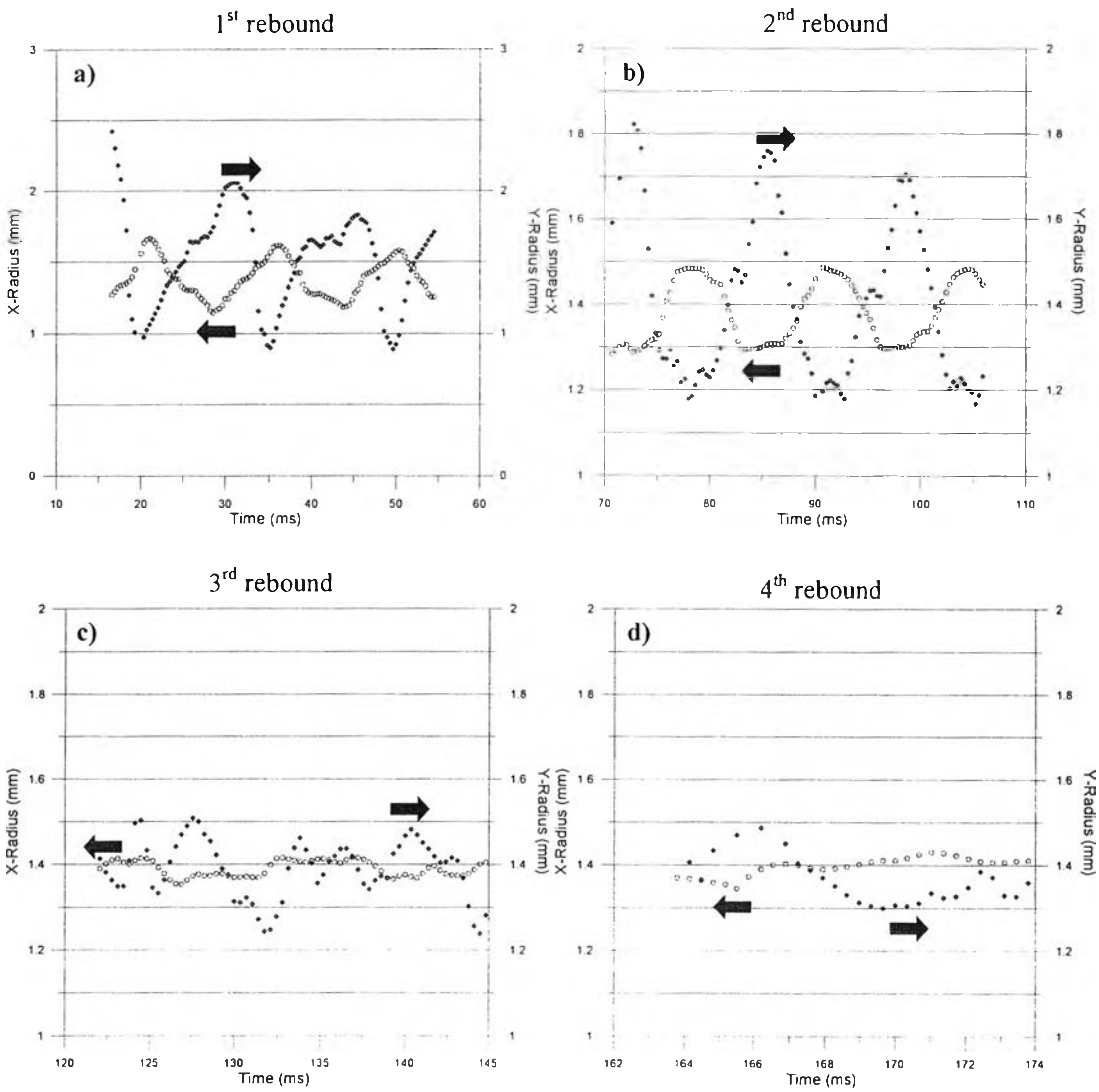


Figure. 4.5 The change of radius in the x and y radius with time of the water droplet having size of 10.9691 mm^3 with an initial impact velocity of 0.4362 m/s onto CF_4 plasma-treated polypropylene film coated on glass surface during a) 1st rebound, b) 2nd rebound, c) 3rd rebound, and d) 4th rebound

As shown in Figure 4.5 and in Table 4.2, for the 1st and 2nd rebounds, the water droplet have quite smooth pattern of oscillation but there are more complex pattern for 3rd and 4th rebounds suggesting that the impact process is quite complex, resulted from the internal liquid movement which made water movement.

Table 4.2 The change in the x and y radius of a water droplet having size 10.9691 mm^3 with initial impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on glass surface during a) y radius, b) x radius.

a.	Minimum radius (mm)	Maximum radius (mm)	Average radius (mm)	STD
Initial Stage	1.3222	1.4294	1.3594	0.0339
1st Rebound	1.1479	1.6628	1.3860	0.1340
2nd Rebound	1.2838	1.4861	1.3805	0.0736
3rd Rebound	1.3536	1.4164	1.3902	0.0183
4th Rebound	1.3454	1.4100	1.3973	0.0227

b.	Minimum radius (mm)	Maximum radius (mm)	Average radius (mm)	STD
Initial Stage	1.2948	1.5009	1.4110	0.0637
1st Rebound	0.8894	2.4212	1.5249	0.3440
2nd Rebound	1.1675	1.8222	1.4089	0.1930
3rd Rebound	1.2380	1.5085	1.3899	0.0684
4th Rebound	1.2998	1.3274	1.3620	0.0531

4.3 Peak of Maxima

When the enlargement of the movement of center of mass of rebounding droplet in the air at the maximum period was done, it was found that there were several peaks of maxima in every rebound.

Figure.4.6 shows the change of the center of mass of each rebound and Figure.4.7 shows the images of movement of center of mass during 1st rebound. Interestingly, there were several peaks of maxima. These peaks of maxima occurred because the internal liquid movement which make the alternate change in diameter in two direction. When the water droplet went to the maximum height the top portion reached the maximum height first and made the first peak. Afterward, the top portion started to fall down at the same time that the bottom portion that follow the top portion went up and pushed the top portion up again before both portion started to fall down together. For the 2^{nd} – 4^{th} rebounds, the more complexity of internal liquid movement made not just only two peaks of maxima but several peak of maxima.

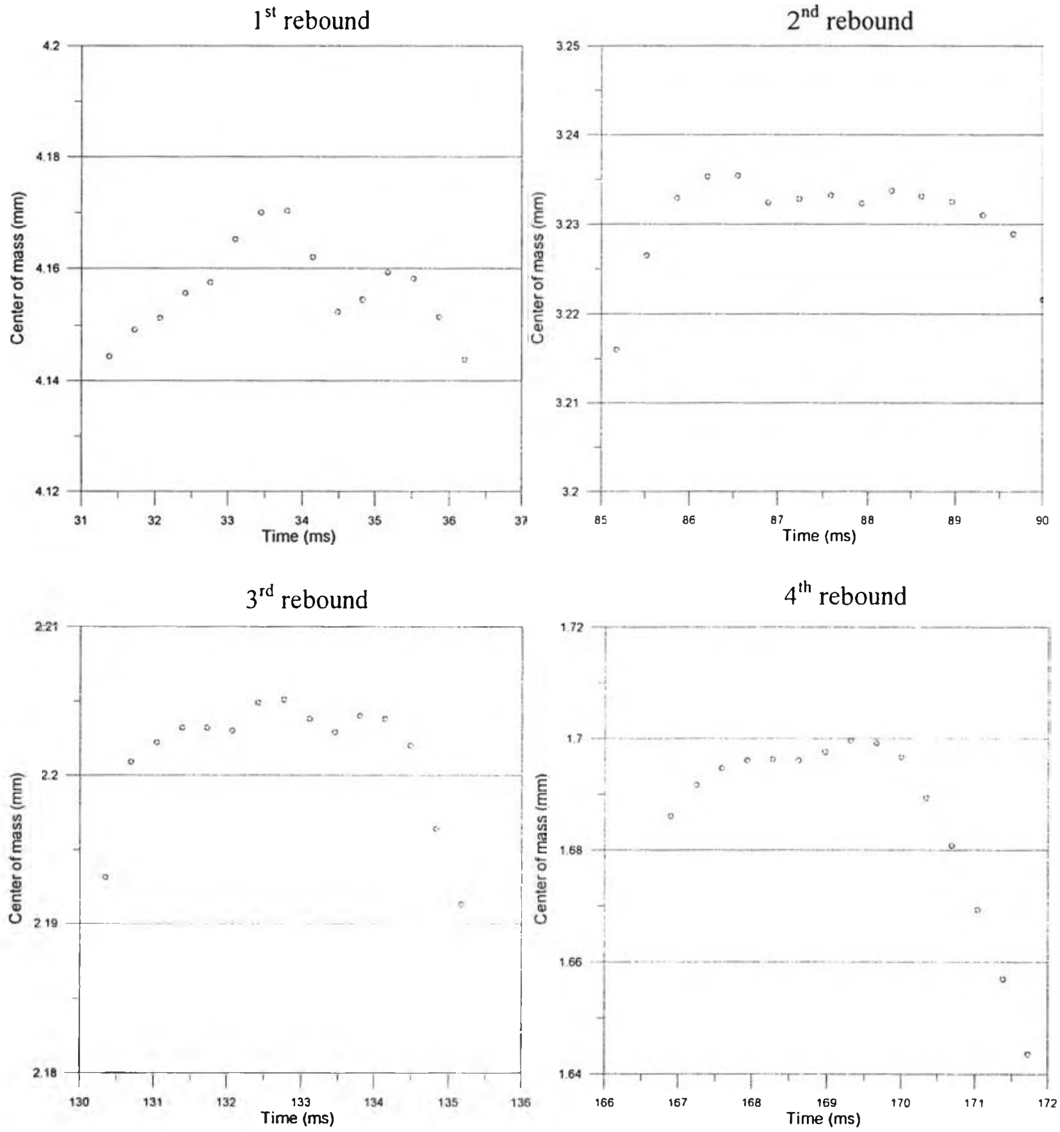


Figure 4.6 Peaks of maxima of a water droplet having 10.9691 mm^3 with impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface

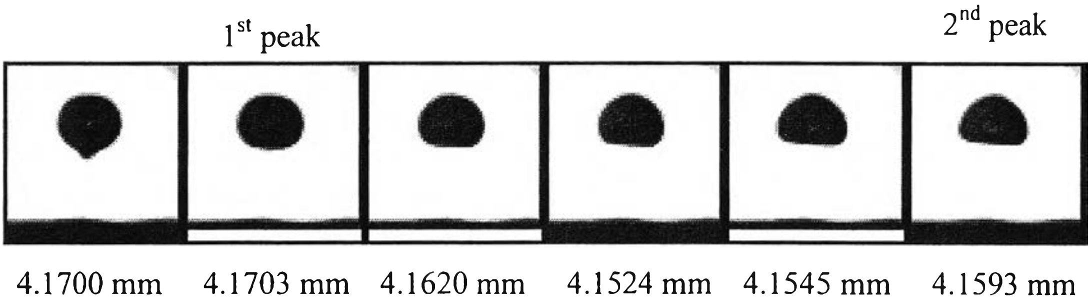


Figure 4.7 The change of center of mass with time of a water droplet having 10.9691 mm^3 with impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface during the first rebound

4.4 The Change in Projection Area

The fluctuation of water droplets 2D-volume was affected by the projection area due to the droplet volume deformation. As results from the taken image, image was taken from front view parallel to surface. The taken image was in 2-dimentions which lie on x and y axis. The water droplet simulation was relied on x and y direction only without concerning droplet size in z direction. Once water droplet impact onto a solid surface, radius in x axis was shrink but it was enlarge in y and z direction.

As shown in Figure 4.8, the projection area varies during both impact period and rebound period. During the impact period, the water droplet spreads on the solid surface and reaches the maximum spreading. When the droplet reaches the maximum spreading, the droplet's radius in the y axis decreases whereas the radius in both in x and z direction increase. As a result, the projection area of the water droplet decreases. Figure 4.9 shows the image of the water droplet at the maximum spreading and the recoil phases. Figure 4.10 shows the same pattern of the change in both volume and projection area of the water droplets of each rebound.

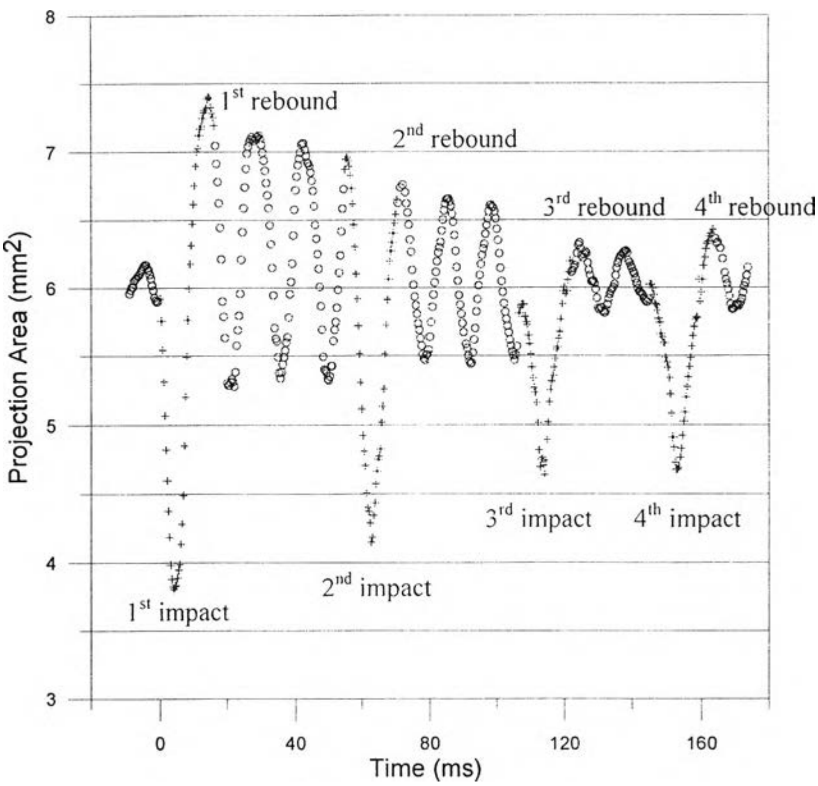


Figure 4.8 The change in projection area with time of a water droplet having 10.9691 mm^3 with initial impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface

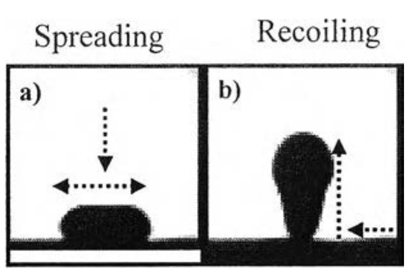


Figure 4.9 Image of water droplet having 10.9691 mm^3 with initial impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface of droplet volume during 1^{st} impact at a) spreading phase and b) recoiling phase

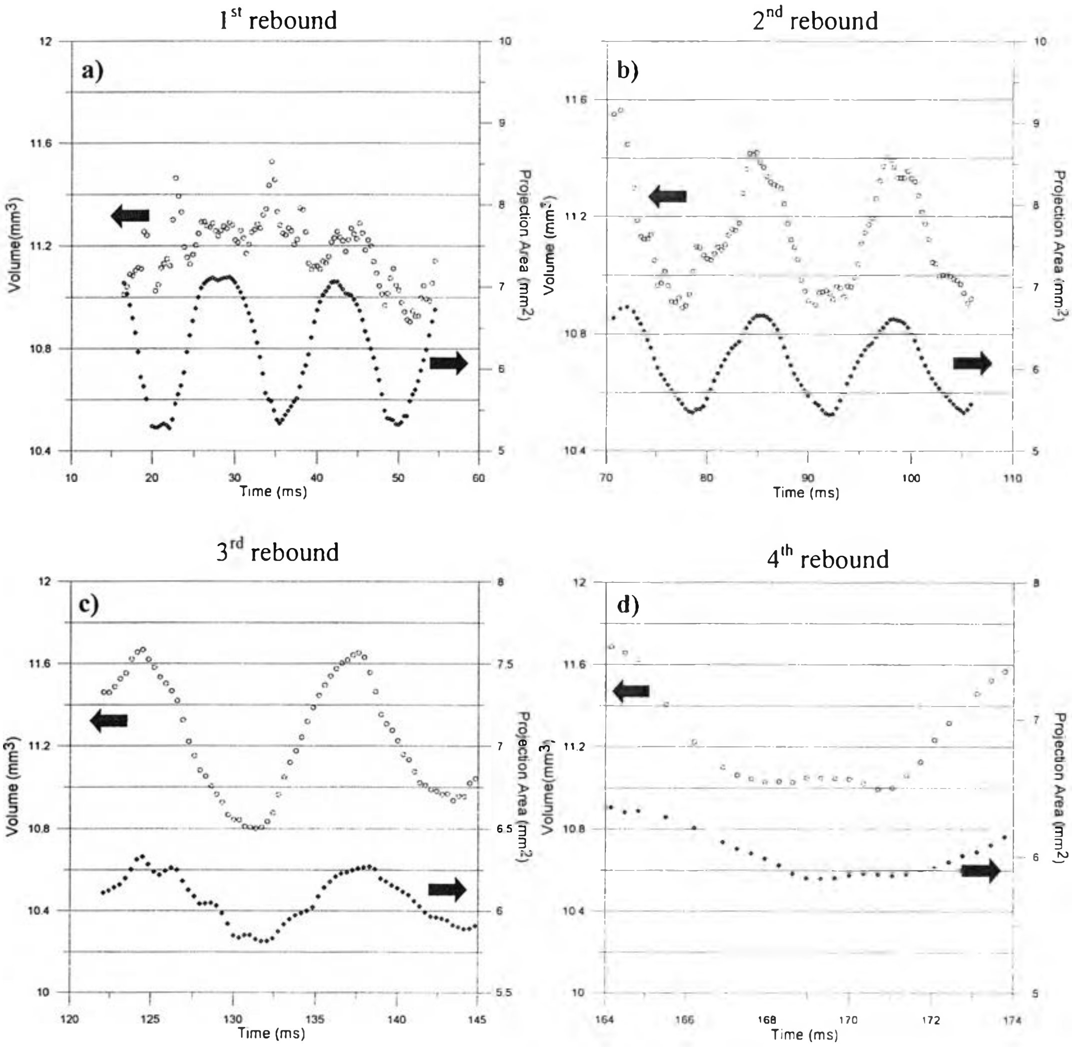


Figure 4.10 The change of projection area and droplet 2D-volume with time of water droplet having size 10.9691 mm^3 and initial impact velocity 0.4362 m/s onto plasma-treated polypropylene film coated on glass surface during a) 1st rebound, b) 2nd rebound, c) 3rd rebound, and d) 4th rebound

Figure 4.11 shows the shape transformation during the 1st rebound and the 2nd rebound.

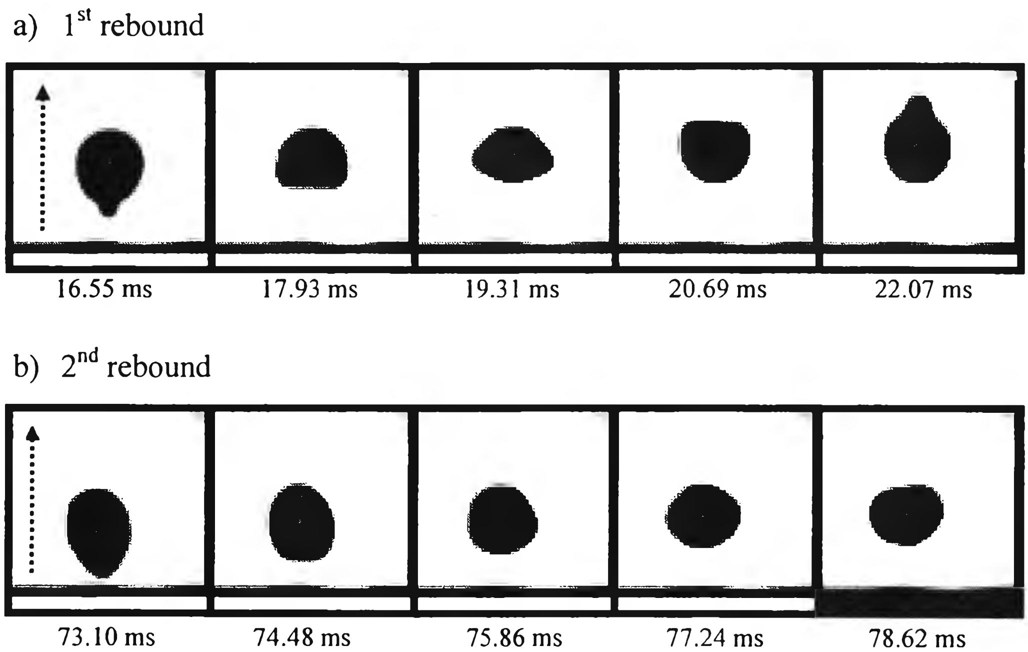


Figure 4.11 Image of water droplet having 10.9691 mm^3 with initial impact velocity of 0.4362 m/s onto the plasma-treated polypropylene film coated on glass surface during a) 1^{st} rebound and b) 2^{nd} rebound

4.5 The Change in Center of Mass in Horizontal Direction

Figure 4.12 shows the deviation of the center of mass of the water droplet to the left side and the decrease of center of mass with increasing number of rebound. It was noticed that for any water droplet impact onto the studied surface, the center of mass in x direction moved a little bit to the left of images. This occurred due to the unbalance of the mass of water droplet between left and right sides. The unbalance of mass resulted from the internal liquid movement which made water impact with some angle deviation from the first impact. The higher the number of impacts, the greater the water internal liquid movement.

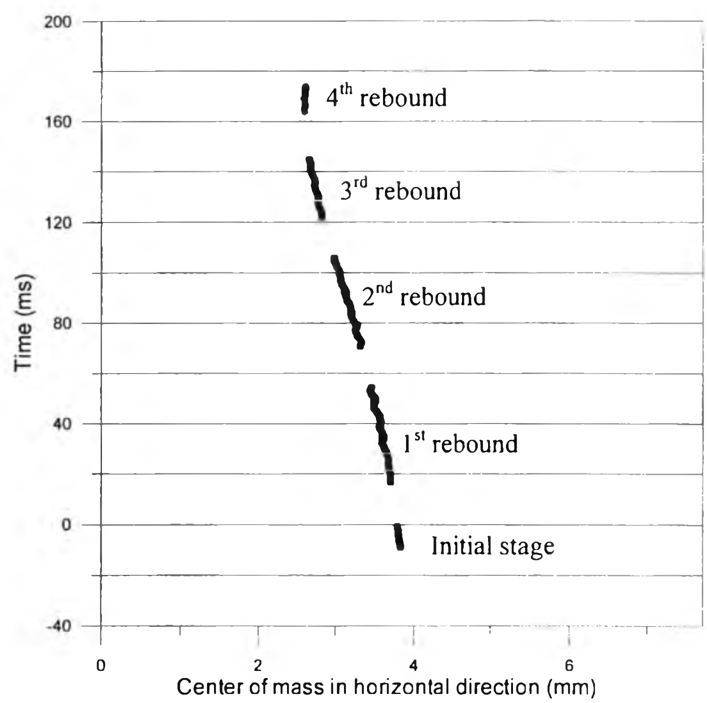


Figure 4.12 The change in center of mass in horizontal direction with time of water droplet having 10.9691 mm^3 volume with initial impact velocity of 0.4362 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface

Moreover, the studied surface with super-hydrophobic properties shows high ability to repel the water droplet to obtain several rebounds. The surface appears very slippery.

4.6 Energy Loss during impact process

During the falling of a water droplet in the air, there is some energy loss as the result of friction. However, this friction loss by air can be considered negligibly as compared to other energy losses. Hence, one can assume the initial energy as the potential energy is a maximum level in the system while the initial kinetic energy is zero. When the water droplet just contacts the solid surface, the potential energy decreases to a zero level but the kinetic energy of the water droplet increases to the maximum level (equal to the initial potential energy). As show in figure 4.12, the maximum height of any rebound is lower than its previous rebound, suggesting that the energy loss occurs during the impact process. The energy dissipation may be by three reasons of the air friction, the internal liquid movement and the solid friction. Among the three factors, the air friction is relatively very small.

4.7 Effect of Droplet Size

The effect of droplet size was studied by varying the initial volume of water droplets (or droplet volume). The change in a water droplet was done by using different needle sizes. The smaller the needle diameter, the smaller the water droplet volume. In this study, the initial volume of water droplets was varied from 5.9650, 10.9691, and 12.6049 mm^3. Figure 4.13 shows the effect of the initial size of water droplets on the impact process.

Both water droplet with 5.9650 and 10.9691 mm3 showed 4 rebounds while the water droplet with the highest size has only 2 rebounds. Interestingly, for any give rebound, the maximum rebound height decreased with increasing water droplet size. The lower the maximum rebound height means the greater the energy loss along both impact and rebound process.

During the impact process, the energy loss can be resulted with several reasons.

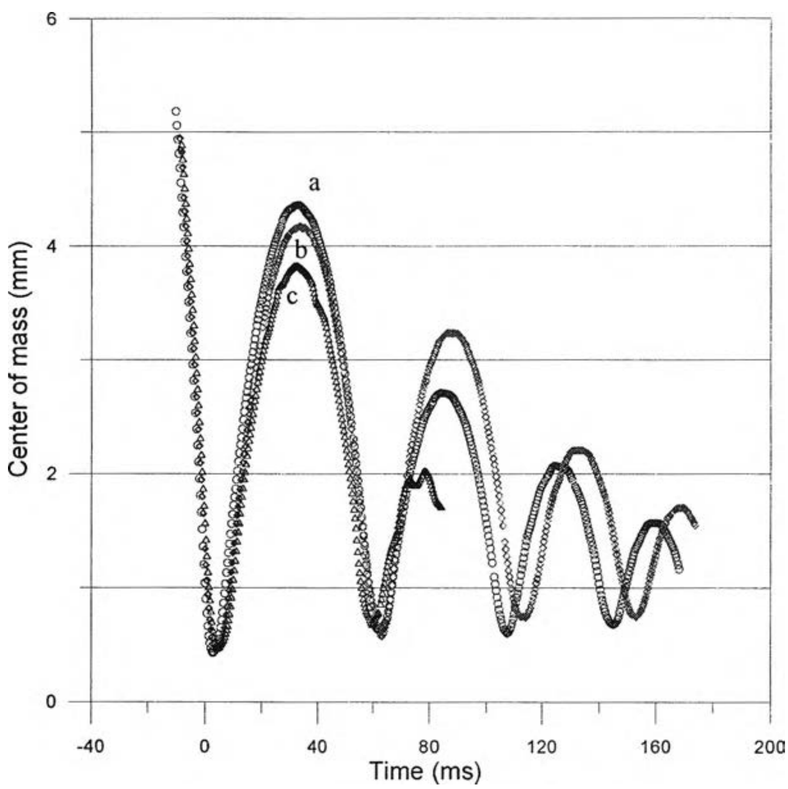


Figure 4.13 The change of center of mass with time of a different initial sizes of water droplets, at initial impact height of 10 mm onto the CF_4 plasma-treated polypropylene film coated on a glass surface: a) (o) 5.9650, b) (◇) 10.9691, and c) (Δ) 12.6049 mm^3

Table 4.3 Impact time and rebound time of the 1st impact and 1st rebounds of a water droplet onto the CF_4 plasma-treated polypropylene film coated on a glass surface with different droplet sizes.

Droplet volume (mm^3)	1st impact time (ms)	1st rebound time (ms)
5.9650	10.6897	45.8621
10.9691	16.2069	37.9310
12.6049	18.2759	36.2069

Table 4.3 shows the effect of water droplet size on impact time and rebound time. Both the first impact time and the first rebound time decreased significantly with incoming water droplet size. The results can be explain in that an increase in water

droplet size increases both the weight and the energy loss to the surface as well as to the internal liquid.

Table 4.4 The 1st maximum rebound height and the 1st minimum impact height of water droplet onto plasma-treated polypropylene film coated on a glass surface at different droplet sizes.

Droplet volume (mm^3)	1st maximum rebound height (mm)	1st minimum impact height (mm)
5.9650	4.3594	0.4306
10.9691	4.1703	0.4477
12.6049	3.8288	0.4724

As shown in Table 4.4, the water droplet size affects the minimum impact height as well as the minimum rebound height. Even though the initial impact velocity was nearly the same but the minimum impact height was not the same. The water droplet with a smaller volume has a smaller radius once it deforms during the impact its and center of mass lower down more than bigger droplet as compare to 5.9650 and 12.6049 mm^3 droplet size.

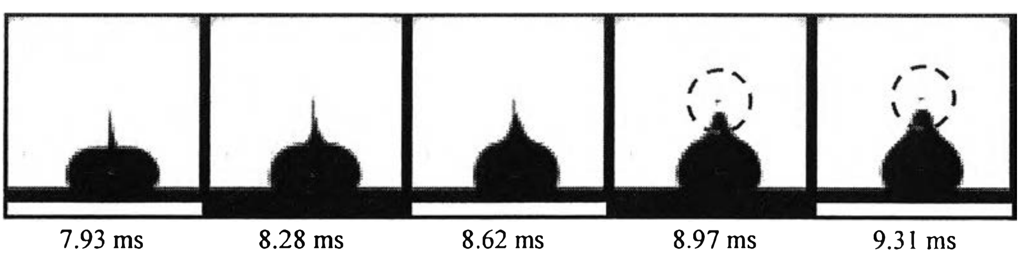


Figure 4.14 Small droplet splitting out during the 1st impact of a water droplet having 12.6049 mm^3 with impact velocity of 0.4344 m/s onto the CF_4 plasma-treated polypropylene film coated on a glass surface

Interestingly, the water droplet with the highest size of 12.6049 mm3, there is a small drop splitting out during the first rebound as shown in Figure 4.14. This splitting occurs during the recoiling process. The recoiling process takes place after the water droplet reaches maximum spreading. Then the flow direction of the internal liquid changes from outward to inward to the center of droplet. So, the flow from every radial direction hits at the same time then ejects a small water particle out from the water droplet.

As shown in Figure 4.15 and Table 4.5, the larger the water droplet volume, the faster the spreading and receding velocity. When the water droplet has high enough receding velocity, a small water particle can eject out from the water droplet.

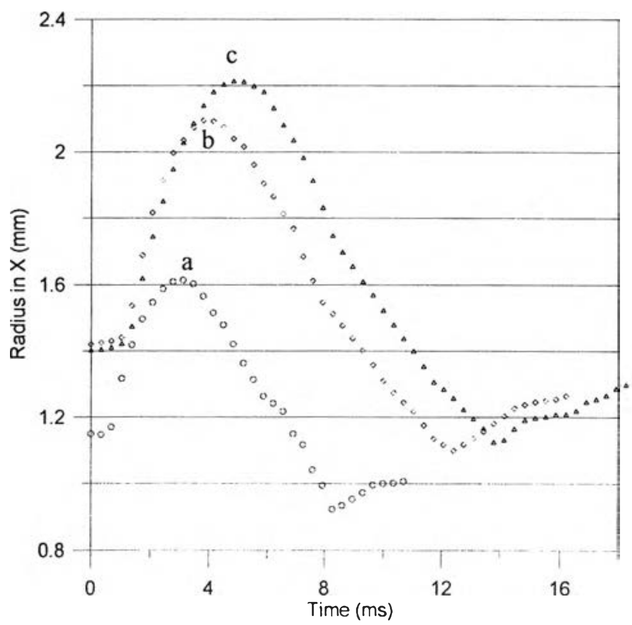


Figure 4.15 The change in radius in X direction with time of droplet having different size during 1st impact process a. (o) 5.9650, b. (◇) 10.9691, and c. (Δ) 12.6049 mm^3

Table 4.5 Spreading and receding velocity of droplet having different size during 1st impact process

Droplet volume (mm^3)	*Spreading velocity (m/s)*	*Receding velocity (m/s)*
5.9650	0.2423	- 0.1304
10.9691	0.2688	- 0.1354
12.6049	0.2958	- 0.1389

As shown in Figure 4.16 and Table 4.6, the smallest size of 5.9650 mm^3 of droplet gives the oscillation with the highest number of loops but with the smallest amplitude as compare to the two larger sizes. This is because a smaller droplet size can rebound with a greater rebounding height but a shorter time per loop as compared to the bigger size of droplet that took a shorter rebounding time and a longer time per loop.

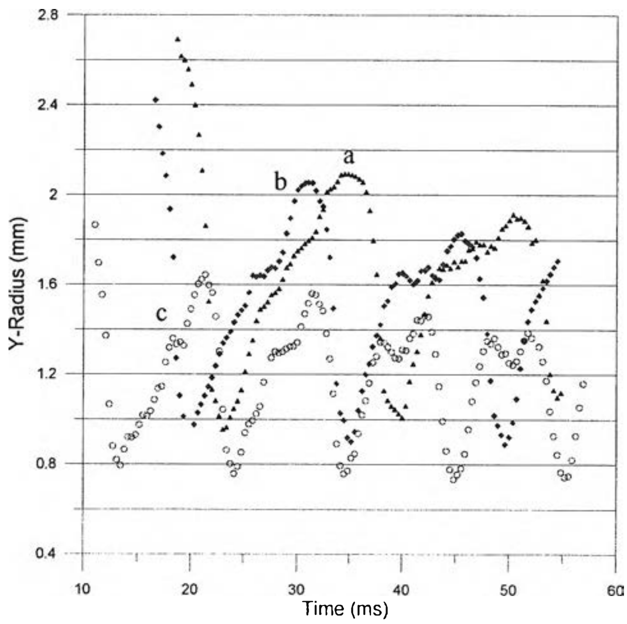


Figure 4.16 The change in radius in y direction with time of rebounding droplet having different sizes during the 1st rebound process a. (o) 5.9650, b. (◇) 10.9691, and c. (Δ) 12.6049 mm^3

Table 4.6 Average radius in Y direction and standard deviation of droplet having different sizes during the 1st rebound process.

Droplet volume (mm^3)	*Average radius in Y (mm)*	*STD*
5.9650	1.1831	0.2578
10.9691	1.5249	0.3440
12.6049	1.6557	0.4005

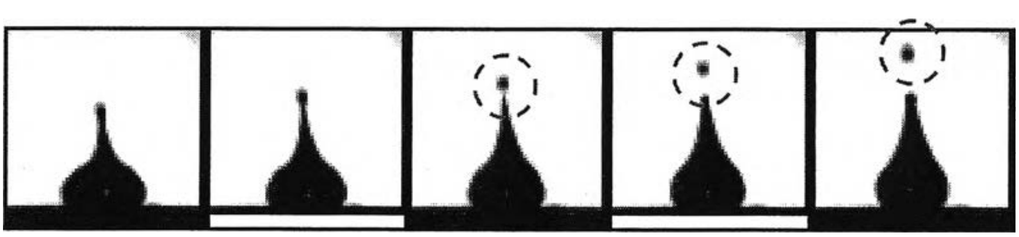
4.8 Effect of Droplet Impact Velocity

The droplet impact velocity is one of the fundamental variables affecting the impact phenomena. The size of water droplets was controlled by using different sizes of needles, Table 4.7 shown the initial impact velocity as a function of water droplet volume. Impact height was set at two different heights of 10 and 20 mm from surface. At the initial stage, it appear that even droplet at initial stage is look spherical than other stage but actually it had little vibration due to air barrier.

As shown it Figure.4.18, the water droplet with an impact velocity of 0.6476 m/s produces a secondary droplet with 0.0444 mm^3 volume or only 0.4% of the original droplet volume. The splitting occurs during the 1st impact stage recoiling process, as indicated in Figure.4.18. After splitting, the rest of droplet continuously rebounded on the surface for 5 times before it reached the equilibrium stage. The secondary droplet splitting out moved out the image frame and toughed the tip of the needle. It means that this secondary droplet can rebound even higher than its original water droplet.

Table 4.7 Initial impact velocity of water droplet onto plasma-treated polypropylene film coated on a glass surface with different impact velocity by varying volume of water droplet.

Droplet volume (mm^3)	Initial impact velocity (m/s)
11.0641	0.6476
10.9691	0.4362



7.93 ms 8.28 ms 8.62 ms 8.97 ms 9.31 ms

Figure 4.17 Small droplet came off during 1st impact of water droplet having size 12.6049 mm^3 with impact velocity 0.6476 m/s onto CF_4 plasma-treated polypropylene film coated on a glass surface

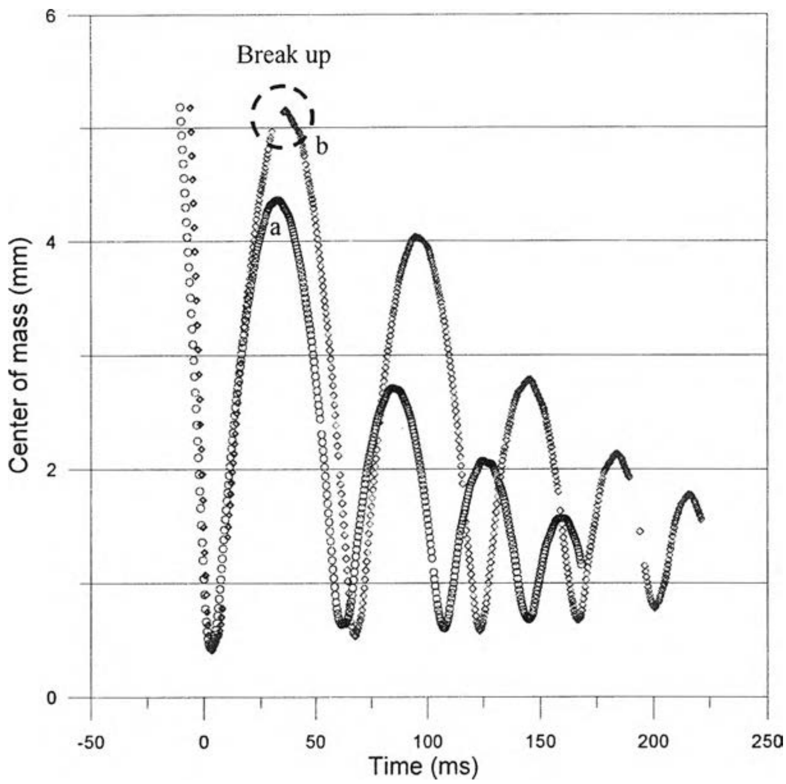


Figure 4.18 The change of center of mass with time of water droplet having different sizes onto CF_4 plasma-treated polypropylene film coated on a glass surface a. (o) V = 10.9691mm3 v 0.4362 m/s, b. (◇) V =11.0641, v = 0.6476 m/s

From Table 4.8, a water droplet with higher impact velocity can rebound higher than that with lower impact velocity. Whereas the minimum impact height decreases with increasing impact velocity. The result can be explained the same way as the effect of droplet size

Table 4.8 The 1st maximum rebound height and 1st minimum impact height of water droplet onto the CF_4 plasma-treated polypropylene film coated on a glass surface with different impact velocity

Impact velocity (m/s)	1st maximum rebound height (mm)	1st minimum impact height (mm)
0.6476	5.1508	0.4098
0.4362	4.1703	0.4477

As shown in Figure 4.19 and Table 4.9, the water droplet with 0.6476 m/s initial impact velocity has higher spreading and receding velocity which is high enough to eject a secondary droplet into the air during 1st impact process and the remaining part still rebounds on the surface for 5 times. The greater the spreading and the receding velocity, the higher the possibility of the droplet can eject during the 1st impact process.

Figure 4.19 The change in radius in X direction with time of a water droplet having different impact velocity during the 1st impact process a. (o) 0.6476, b. (◇) 0.4362 m/s

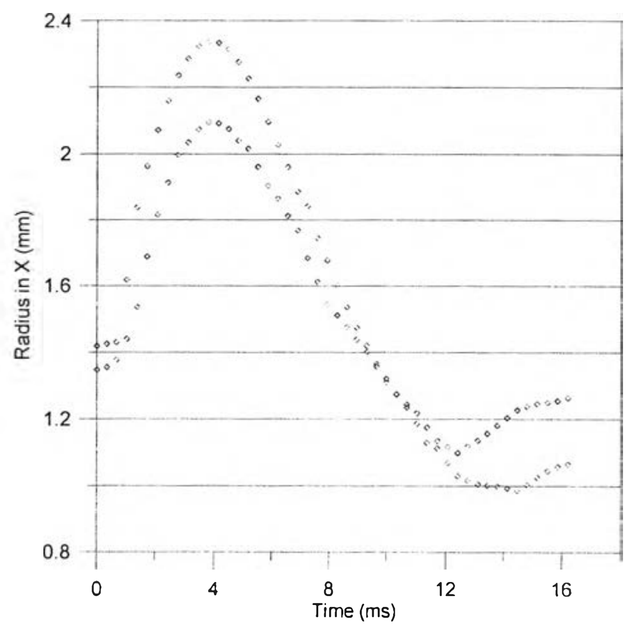


Table 4.9 Spreading and receding velocity of a water droplet having different initial impact velocity during 1st impact process.

Impact velocity (m/s)	*Spreading velocity (m/s)*	*Receding velocity (m/s)*
0.6476	0.2688	- 0.1354
0.4362	0.4533	- 0.1756

The rebounding droplet in the air, the droplet with higher initial impact velocity contains higher kinetic energy inside liquid body. It resulted in higher internal liquid movement which stretching water droplet more both in vertical and horizontal directions but this amount of energy is not enough to break surface energy of water droplet. The faster the initial impact velocity the greater the amplitude of oscillation of rebounding water droplet.

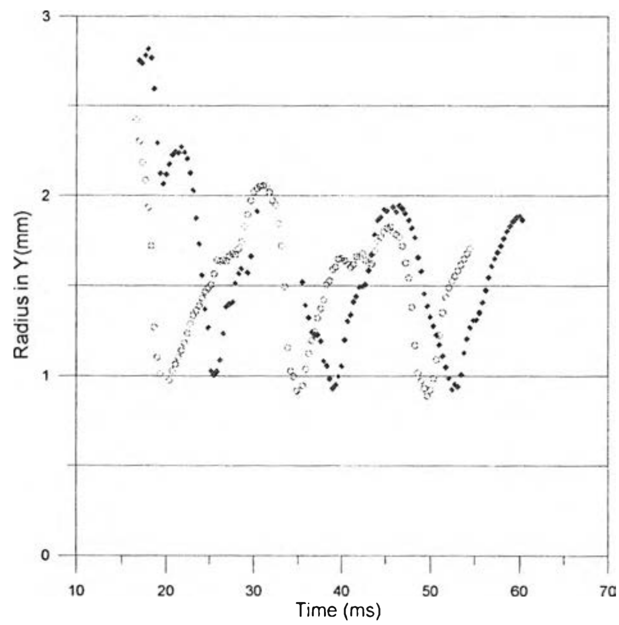


Figure 4.20 The change in radius in Y direction with time of rebounding droplet having different initial impact velocity during 1st rebound process a. (o) 10.9691 and b. (◇) 11.0641 mm^3

Table 4.10 Average radius in Y direction and standard deviation of droplet having different initial impact velocity during 1st rebound process.

Droplet volume (mm³)	*Average radius in Y (mm)*	*STD*
10.9691	1.5249	0.3440
11.0641	1.6063	0.4612

4.9 Energy Balance

Energy balance was performed in order to quantify the energy during the impact process. As mentioned in the previous section, droplet size and droplet velocity influenced of the impact process in terms of energy loss. The larger the droplets size, the longer the impact time and also the greater the energy loss. Table 4.11 show the changes in energy and energy loss of the impact process at different sizes of water droplet and different rebounds. The ratio of energy loss is calculated based on the potential energy at the maximum rebound height. During the 1st rebound, the ratio of energy loss of water droplets with different sizes of 12.6049, 10.9691, and 5.9650 mm^3 was 0.6171, 0.5830 and 0.5641 respectively. The larger the size of water droplet, the higher the ratio of energy loss.

Table 4.11 Maximum height, Potential energy, energy loss, and ratio of energy loss

a. V = 12.6049 mm^3 and v = 0.4344m/s,
b. V = 10.9691 mm^3 and v = 0.4362m/s
c. V = 5.9650 mm^3 and v = 0.4541m/s,
d. V =11.0641 mm^3 and v = 0.6476 m/s

a.	**Maximum Height (mm)**	**Potential Energy (mJ)**	**Energy loss (mJ)**	**Ratio of Energy loss**
Initial Stage	10.0000	1.2338		
1st Rebound	3.8288	0.4724	0.7614	0.6171
2nd Rebound	2.0266	0.2500	0.2224	0.1802

b.	**Maximum Height (mm)**	**Potential Energy (mJ)**	**Energy loss (mJ)**	**Ratio of Energy loss**
Initial Stage	10.0000	1.0737		
1st Rebound	4.1703	0.4477	0.6259	0.5830
2nd Rebound	3.2354	0.3474	0.1004	0.0935
3rd Rebound	2.2051	0.2368	0.1106	0.1030
4th Rebound	1.6996	0.1825	0.0543	0.0506

c.	**Maximum Height (mm)**	**Potential Energy (mJ)**	**Energy loss (mJ)**	**Ratio of Energy loss**
Initial Stage	10.0000	0.5839		
1st Rebound	4.3594	0.2545	0.3293	0.5641
2nd Rebound	2.7125	0.1584	0.0962	0.1647
3rd Rebound	2.0714	0.1209	0.0374	0.0641
4th Rebound	1.5666	0.0915	0.0295	0.0505

d.	Maximum Height (mm)	Potential Energy (mJ)	Energy loss (mJ)	Ratio of Energy loss
Initial Stage	20.0000	2.1659		
1st Rebound	5.1508	0.5556	1.6103	0.7435
2nd Rebound	4.0315	0.4348	0.1207	0.0557
3rd Rebound	2.7884	0.3008	0.1341	0.0619
4th Rebound	2.1317	0.2299	0.0708	0.0327
5th Rebound	1.7752	0.1915	0.0385	0.0178

The impact velocity influenced the energy loss since the faster the droplet impact, the wider the droplet spread on the solid surface, suggesting that the greater the friction loss to the surface. Moreover, the system loses some part of energy with the ejection of secondary droplet after recoiling. As shown Table 4.11 the 1st rebound droplet with 0.6476 m/s velocity had the ratio of energy loss of 0.7435 which is greater than that with 0.4362 m/s that had the ratio of energy loss of 0.5830.