

**DYNAMICS OF WATER DROPLET SPINNING AND
ROLLING ON INCLINED SUPERHYDROPHOBIC
WEDGED CHANNEL**

BY

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[This work is dedicated to my beloved mother; late Hajara Abdullah. Her love, words and advice will forever remain in my memory. May we live together in Al-jannatul Firdaus.]

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LIST OF ABBREVIATIONS

ALE	:	Arbitrary Lagrangian-Eulerian
CLS	:	Conservative level set
CLSMOF	:	Conservative level set moment of fluid
CLSVOF	:	Conservative level set volume of fluid
LS	:	Level set
NS	:	Navier-Stokes
ODE	:	Ordinary differential equation
PC	:	Polycarbonate
PV	:	Photovoltaic
SEM	:	Scanning electron microscope
VOF	:	Volume of fluid
2D	:	Two-dimensional
3D	:	Three-dimensional

Symbol	:	Definition	:	Unit
γ_{LV}	:	Surface tension	:	N/m
γ_{SL}	:	Interfacial energy	:	N/m
γ_{SV}	:	Surface free energy	:	N/m
R	:	Droplet radius	:	m
m	:	Droplet mass	:	kg
E''_{ad}	:	Surface adhesion energy	:	Nm
A_{wet}	:	Wetted area	:	m ³
h	:	Height of center of mass	:	m
α	:	Inclination angle	:	°
g	:	Gravitational acceleration	:	m/s ²
F_{ad}	:	Adhesion force	:	N
F	:	Friction	:	: N
ϕ	:	Wedge angle	:	°
V	:	Droplet volume	:	m ³
v	:	Velocity	:	m/s
a	:	Acceleration	:	m/s ²
v_x	:	Velocity along x direction	:	m/s

v_y	:	Velocity along y direction	:	m/s
v_z	:	Velocity along z direction	:	m/s
ω	:	Angular velocity	:	rad/s
θ	:	Rotation axis	:	°
N	:	Normal force	:	N
I	:	Moment of inertia	:	kgm ²
α_x	:	Angular acceleration along x	:	m/s ²
α_z	:	Angular acceleration along z	:	m/s ²
t	:	Time	:	s
t^*	:	Dimensionless time	:	1
τ	:	Moment of forces	:	Nm
K	:	Spinning acceleration parameter	:	s ⁻²
ρ	:	Mass density	:	kg/m ³
f	:	Solid fraction	:	1
θ_A	:	Advancing contact angle	:	°
θ_R	:	Receding contact angle	:	°
v_{tot}	:	Total translational velocity	:	m/s

v_{rot}	:	Rolling translational velocity	:	m/s
v_{spin}	:	Spinning translational velocity	:	m/s
v_{slid}	:	Sliding translational velocity	:	m/s
v_{rot}^*	:	Rolling velocity fraction	:	1
v_{spin}^*	:	Spinning velocity fraction	:	1
v_{slid}^*	:	Sliding velocity fraction	:	1
ρ_1	:	Density of air	:	kg/m ³
ρ_2	:	Density of water	:	kg/m ³
μ_1	:	Dynamic viscosity of air	:	Pa.s
μ_2	:	Dynamic viscosity of water	:	Pa.s
σ	:	Surface tension of water	:	N/m
φ	:	Level set function	:	1
ϵ_{ls}	:	Interfacial thickness parameter	:	m
γ	:	Re-initialization parameter	:	: m/s
F_{st}	:	Surface tension force	:	N
F_{wall}	:	Wall force	:	N
θ_w	:	Contact angle of the wetted wall	:	°

ABSTRACT

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Thesis Title : [Dynamics of water droplet spinning and rolling on inclined superhydrophobic wedged channel]

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Performance of most solar energy harvesting devices suffers from environmental effects. This causes deterioration of device performance with progressing time and it becomes particularly critical for photovoltaic panels such that the optical transmittance of top cover reduces by the accumulation of environmental dusts. The solar radiation passing through dusty transparent surfaces undergoes diffused reflection, refraction, and absorption depending largely on sizes and local distribution of dust layer. In addition, high humidity in air allows dissolution of dust compounds on dust particles. The resulting mixture of dust and condensate leads to formation of chemically active film that alters transmittance of the surface to solar electromagnetic spectrum. Hence, removal of dust before condensate film formation on surfaces becomes important. In self-cleaning application for dust removal from surface, the dynamic of droplet on an inclined superhydrophobic surface plays a crucial role. In this study, a coating and solution immersion techniques are developed to hydrophobize glass and polycarbonate surfaces. The rolling and spinning motions of a water droplet on inclined wedge surfaces formed from two hydrophobic plates with different hydrophobic wetting states are examined incorporating three approaches, namely, analytical, experimental and numerical approaches. Analytical method provides a platform for setting the

experimental design and selection of experimental parameters. Velocity and pressure variation in droplet fluid and the contact line dynamics that govern the dust cleaning ability of water droplet are studied via a numerical code. Both analytical and numerical models are validated with the experimental data. The results are analyzed based on rolling and spinning angular velocities as well as translational velocity of droplet on the inclined plane. From the dimensionless area plot, dust cleaning ability of water droplet without spinning is reduced to about 87% as droplet only rolls on dusty surface. This is due to striation-like patterns path in droplet path, which are caused by wobbling nature of rolling droplet. However, spinning of rolling droplet has greatly minimized such striation-like patterns in droplet path and improve dust cleaning ability considerably by 98%.

ملخص الرسالة

الاسم الكامل: مبارك ياكوبو

عنوان الرسالة: ديناميكيات غزل قطرات الماء والدحرجة على قناة إسفينية مائلة للماء

التخصص: علوم حرارية

تاريخ الدرجة العلمية: أبريل 2020

يعاني معظم أجهزة حصاد الطاقة الشمسية من تأثيرات بيئية. يتسبب هذا في تدهور أداء الجهاز مع تقدم الوقت ويصبح حرجًا بشكل خاص للألواح الكهروضوئية مثل أن النفاذية البصرية للغطاء العلوي تقلل من تراكم الغبار البيئي. يخضع الإشعاع الشمسي الذي يمر عبر أسطح شفافة متربة للانعكاس المنتشر والانكسار والامتصاص اعتمادًا كبيرًا على الأحجام والتوزيع المحلي لطبقة الغبار. بالإضافة إلى ذلك ، تسمح الرطوبة العالية في الهواء بإذابة مركبات الغبار على جزيئات الغبار. يؤدي الخليط الناتج من الغبار والمكثفات إلى تكوين غشاء نشط كيميائيًا يغير نفاذية السطح إلى الطيف الكهرومغناطيسي الشمسي. وبالتالي ، فإن إزالة الغبار قبل تكوين طبقة التكتيف على الأسطح تصبح مهمة. في تطبيق التنظيف الذاتي لإزالة الغبار من السطح ، تلعب ديناميكية القطرة على سطح خاروف مائل دورًا حاسمًا. في هذه الدراسة ، تم تطوير تقنيات الغمر بالطلاء والمحول لتلطيف الزجاج وأسطح البولي. يتم فحص حركات التدحرج والغزل لقطرة الماء على أسطح الوتد المائلة المكونة من لوحين مسعورين مع حالات ترطيب مسعور مختلفة تتضمن ثلاث طرق ، وهي النهج التحليلي والتجريبي والعددي. يوفر الأسلوب التحليلي منصة لوضع التصميم التجريبي واختيار المعلومات التجريبية. يتم دراسة تغير السرعة والضغط في سائل القطيرات وديناميكيات خط الاتصال التي تتحكم في قدرة الغبار على تنظيف قطرات الماء من خلال رمز رقمي. يتم التحقق من صحة كل من النماذج التحليلية والعددية مع البيانات التجريبية. تم تحليل النتائج بناءً على السرعات الدوارة والغزل والسرعة الانتقالية للقطرة على المستوى المائل. من مؤامرة منطقة بلا أبعاد ، يتم تقليل قدرة تنظيف الغبار من قطرات الماء دون الدوران إلى حوالي 87٪ حيث تتدحرج القطرات فقط على سطح مترب. ويرجع ذلك إلى مسار الأنماط الشبيهة بالتخطيطات في مسار القطيرات ،

والتي تنتج عن تذبذب طبيعة القطيرات المتدحرجة. ومع ذلك ، فإن غزل القطرات الدوارة قد قلل إلى حد كبير من هذه الأنماط الشبيهة بالخط في مسار القطرات وتحسين قدرة تنظيف الغبار بشكل كبير بنسبة 98 %.

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Global energy demand

Owing to need for reliable and sustainable energies, researches are conducted across various fields of human endeavor, to improve the performance of the existing systems, and more so, to find other sources as alternatives to the existing ones. Energy policies have been put in place to address the issue of greenhouse gas emission while maintaining sustainable economic growth. The global energy demand is projected to grow by 60% from 2002 to 2030. with an average annual growth of 1.7%. Oil remains the largest source of fuel in the global energy mix, despite its share is projected to fall from 36% in 2002 to 35% in 2030 [1].

1.1.2 Sources of CO₂ and its environmental effects

The most common greenhouse gas (GHG) is CO₂ and the major sources of CO₂ are electricity generation, heating and cooling processes which account for about 32% of the emission globally, and transportation which accounts for about 17%. Other sources of CO₂ emission globally are land-use change and forestry (24%), Manufacturing and construction

(13%) [2]. Although the planet requires some level of warmth to sustain life, however, high rise in temperature that results from global warming might be detrimental to live the supporting ecological cycles. Some of the effects that result from CO₂ emission are given in Table 1.1.

Table 1.1: Environmental impacts of the conventional energy system [3].

Energy source	Inherent		Avoidable	
	Global	Local	Global	Local
Coal	CO ₂	Mining	Acid rain	Air pollution
Oil	CO ₂		Ocean pollution	Air pollution, local water resources
Gas	CO ₂		Greenhouse gas due to leaking pipelines	
Hydropower		Aquatic ecosystem/competition with other water usage		Aquatic ecosystem/competition with other water usage
Nuclear	Non-proliferation	Accidents/political stability		Radioactive

1.1.3 Importance of Solar and other renewable energies

Renewable sources of energy (such as solar, wind, hydropower, biomass, geothermal etc) have the highest environmental benefits and also replenished on the human time scale [4]. The most abundant of all renewable energy sources is solar; in the form of solar heat and light. However, solar energy is harvested by optical surfaces which require zero barriers with the incoming solar radiation. So far, solar energy is the cheapest, cleanest and the most available source of energy. No hazard is associated with the production and consumption of solar energy. Therefore, is seen to improve the quality of life on earth. The

forecast for global fossil fuel scarcity has increased the demand for the solar energy source [5].

1.1.4 Challenges of Solar energy harvesting in the Middle east

The atmosphere consists of the mixture of gases, dust and some other suspended material, therefore exposed surface are always bound to have some particulate deposits. Recent changes experienced in the meteorological conditions especially in the Middle East has resulted in the formation of frequent dust storms. Deforestation results in compaction loss of the topsoil which results in suspension of such loose soil particles into the atmosphere forming dust storms [6]. This dust, however, settles on solar energy collecting surfaces such as Photovoltaic panels, thereby reducing the potential features of such surfaces. Efforts have been placed to restore the potential feature of such surfaces via cleaning. However, that required a lot of energy as well as water consumption. Hence, the scarcity of water, especially in the urban areas, necessitates the need for the attention development of self-cleaning surfaces, which will considerably reduce the effort of dust removal and result in improved efficiency of solar energy harvesting.

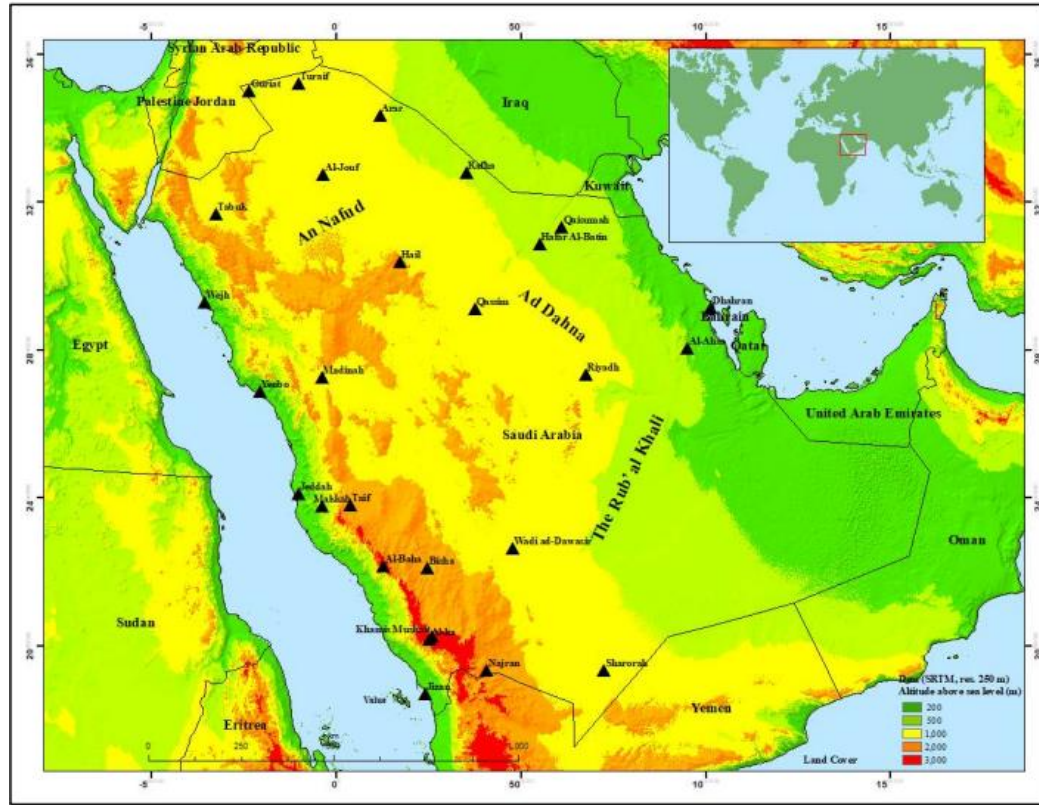


Figure 1.1: Relief map of Arabian peninsular including major cities and desert as well as in situ dust storm measurement stations [7].

Considering the global climatic condition, Saudi Arabia is one of the driest countries in the world with less than 100mm average annual precipitation. During summer the temperature rises to an average of 50°C while in the winter season, the temperature falls to 8-17°C depending on the location [8]. Most of its territories covered by a vast arid climate type with an exception of the Southern part of the country. The largest desert in the Arabian peninsular is the Empty Quarter (or Ruba'al Khali) which dominates about 650,000 km³ located in the Southern part. Other important deserts include; The An Nafud desert, located in the north with an area cover of 57,000 km³, The Ad Dahna desert located in the east with an area cover of 1450 km³ [7].

1.1.5 Factors that influence dust settling

Dust settling on PV panel and other solar collecting surfaces is influenced by various parameters, Various parameters. Some of the major parameters that influence the dust settling include; Dust property and characteristics (such as chemical composition, size, shape, density etc.), Wind velocity and direction, ambient temperature, humidity, Glazing surface property, solar panel angle and orientation among other factors [9]. Site characteristics resulting from human activities, type of vegetation, and weather condition are mostly considered as environmental factors. Similarly. The surface property of solar glazing surface places important in dust accumulation. A rough and sticky glass surface is more likely to build up dust than a smooth surface. A horizontal surface has more tendency to accumulate dust than the inclined surface. However, the orientation of the inclined surface to the prevailing wind direction is an important factor that determines the dust accumulation rate [10].

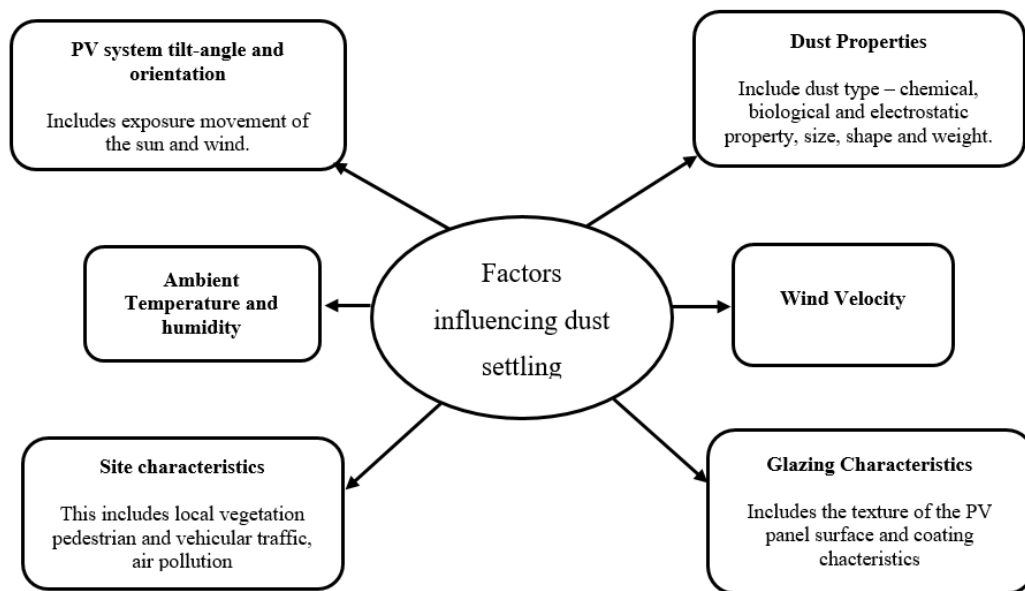


Figure 1.2: Parameters that affect dust settling on the solar PV panel.

In general, high-velocity wind disperses dust and enhance panel surface cleaning while a low and calm wind increases dust deposition rate. However, there are some specific conditions at which the strong wind might increase or decrease dust accumulation. The dispersion of dust due to panel inclination and wind velocity largely depends on the dust characteristics such as; type, size, shape, weight etc [11].

1.1.6 Methods of Dust cleaning

In general, there are 4 types of cleaning methods: Natural method, Electrostatic method, Mechanical method, and Coating method.

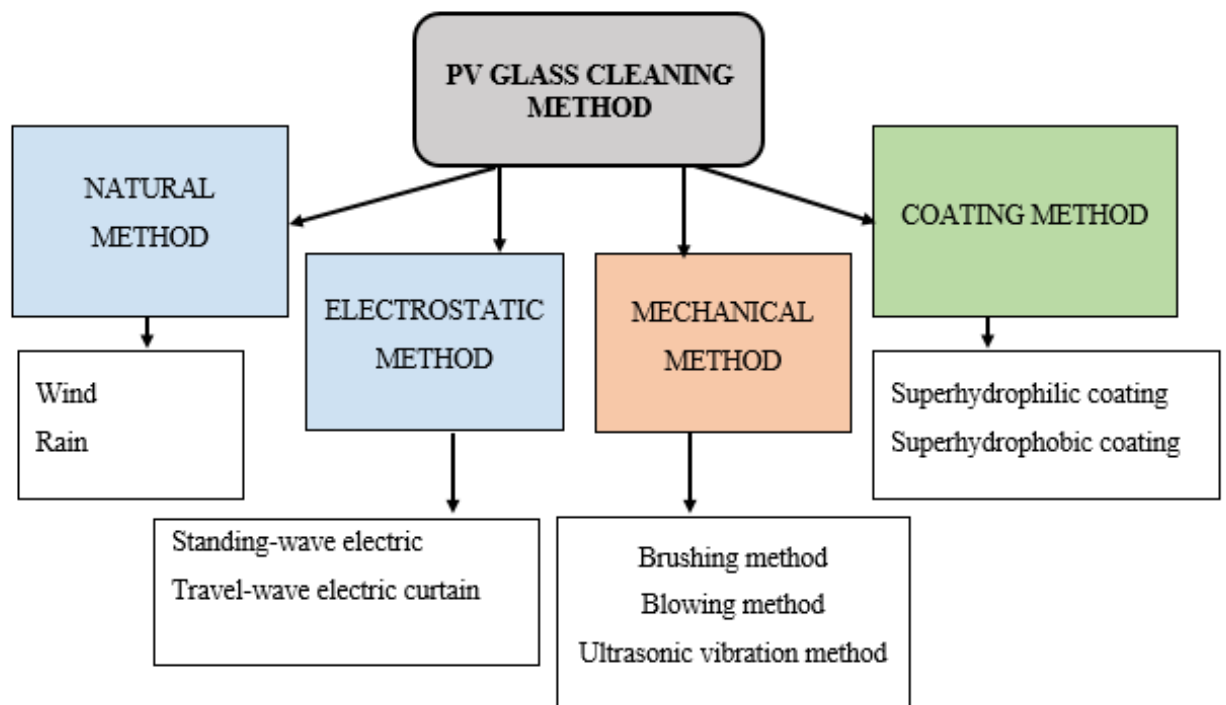


Figure 1.3: Methods of dust cleaning on PV panel

Natural method

In this method, the inclination and orientation of the PV panel are made in such a way that wind or rain easily carry the dust off the surface. This method was studied by Gaier, and it works well for a small size PV panel. However, considering a commercial scale this method is not efficient [12].

Mechanical method

In this method, three different techniques are adopted, which include; Brushing, blowing and ultrasonic vibration. The brushing technique has technical challenges since the surface might get damaged during the cleaning process. It is also difficult for large PV installation and in a highly dusty environment. The blowing technique involves the use of blowing air to take off the dust on the surface. This technique is not efficient for cleaning organic dust [12]. In the Ultrasonic method, vibration waves generated through the piezoelectric effect are used to drive the dust off the PV surface.

Electrical method

This method is first developed by the University of Tokyo. In this method, dust is first electrically charged after which electrostatic field is applied. The applied field tends to create repulsion force which suspends the dust off the surface [13].

Coating method

In the Coating method, a substrate is applied on the PV surface which protects the surface environmental conditions. In this method, the surface properties such as adhesion, wear resistance, wettability, corrosion is altered. coating can be applied to the substrate through

solid, liquid or gas deposit. For hydrophobic surface property, materials such as silane, silicones, nanoparticles are applied which reduce the surface energy. Superhydrophobic surface utilizes rolling droplet or air to remove dust or dirt out of the surface. On the other hand, superhydrophilic surfaces diminish any pollutant through photocatalysis reaction. Coating methods provide a natural way of self-cleaning ability, therefore, requires low cost, low energy consumption, eco-friendly and low maintenance requirement [14].

1.2 Motivation

The dynamics of water droplet towards achieving efficient cleaning becomes an important area of self-cleaning applications. Liquid droplet dynamics becomes critical for various domestic and industrial applications, which includes cleaning and heating/cooling applications [15]. A large area of dust can be effectively cleaned if a droplet rolls down an inclined hydrophobic dusty PV surface. In general, surface cleaning by a rolling and spinning droplet largely depends on the wetting diameter, sliding and spinning rate, and the wetting state of surfaces. For large contact angle hysteresis, droplet rolling is replaced with sliding on the hydrophobic surface. This becomes important for the self-cleaning application of the PV panel. This is because of the fact that rolling velocity becomes much less than translational velocity of rolling droplet.

1.2.1 Hydrophobicity

The generation of such hydrophobic surface is very challenging due to the need for a repetitive arrangement of surface texture morphology which enhances the surface free energy. The hierarchical arrangement of associated with such surface topology is necessary due to the need for air pockets between micro/nanopillars on the hydrophobic surface. Self-cleaning of hydrophobic surfaces by rolling water droplets was presented previously [15,16], and it was successfully demonstrated that the water droplet cleans the hydrophobic surfaces effectively. The natural cleaning of surfaces takes place by rainfall and the impacting and rolling of the droplets on to the surfaces play an important role in the cleaning process.

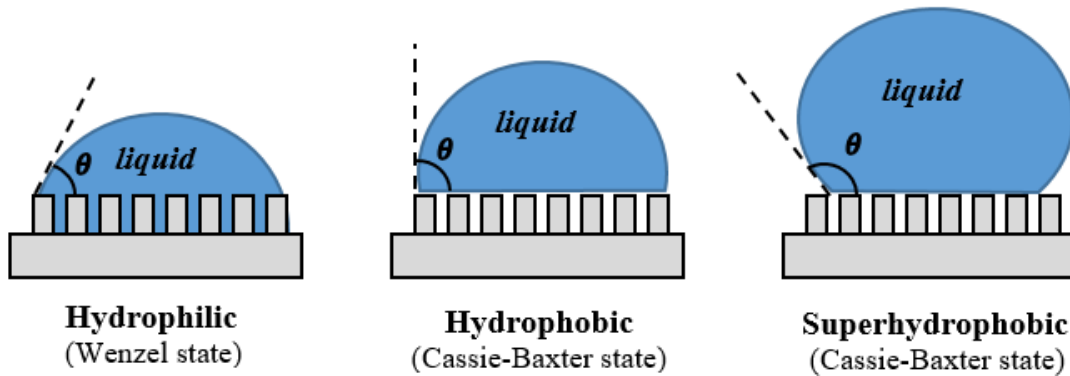


Figure 1.4: Schematic illustration of different wetting states of a liquid droplet on a textured surface

The hydrophobicity (or wetting state) of surfaces can affect the dynamics of droplet impact in various dimensions. Previous analytical, empirical and numerical studies provide useful information on droplet rolling behavior upon its impact on hydrophobic surfaces. Miwa et

al. developed an analytical model that captured the effect of sliding and contact angle for the droplet moving on a hydrophobic surface given by $\cos \theta' = r f \cos \theta + f - 1$, where θ' is the angle on a rough surface, θ is the equilibrium contact angle on a smooth surface, r is the ratio of the side area to the bottom area of the needle, f is the projected area fraction in contact with the liquid [17]. Using the same equation they derived other equation that establishes the relationship between sliding angle and contact angle. Rios et al. found that, for any measured contact angle, the sliding angle of the water droplet on a smooth and nanometric roughed surface can be predicted using an empirical model [18]. Sakai et al. found that sliding acceleration highly influenced the rolling motion of large water droplet, whereas for small droplets sliding acceleration occurred mainly with sliding mechanism [19]. Sakai et al. also found that, on superhydrophobic surfaces, slipping dominates the droplet acceleration. whereas, during sliding on a hydrophobic surface, both slipping and rolling governed the flow speed [20]. Hsieh et al. found that the sliding motion of water droplet is governed by both plane inclination angle as well as adhesion force at the droplet-surface contact [21].

1.2.2 Mechanism of dust cleaning by liquid droplets

The self-cleaning property of the hydrophobic surface allows the dust particles to be easily removed by the rolling and sliding liquid droplet. There are different mechanisms for droplet motion on dusty surfaces reported in the literature. These mechanisms include; impinging, rolling and sliding motions of the liquid droplet.

Impinging droplet

The imping of liquid drop is the most common natural phenomenon which has been studied for more than a century. Although most of the studies were concentrated towards the morphological evolution of the impinging liquid droplet on various surfaces [22]. For the impinging water droplet, only the trailing edge of the droplet can pick up dust particles when the rolls down an inclined surface [23]. Detailed investigations of the self-cleaning surfaces by imping droplet are very few. Furstner reported that water droplets with some initial impacting energy can effectively enhance cleaning on superhydrophobic surfaces [24]. Although the study has not provided the effect of surface properties and the nature of dust on the cleaning ability. The dynamic impact of water droplet might lead to a rebound depending on whether the air packet in the impact air is disrupted. The major driving force behind the transition from non-wetting to a fully wetting state is governed by the dynamic pressure. A Weber number, the ratio of dynamic pressure to capillarity pressure can provide the transition regime of the wetting states [22]. Weber number is the most common dimensionless number that compares the inertia effect and surface tension effect.

$$We_d = \frac{\rho V^2 d}{\sigma} \quad (1.1)$$

where We_d is the Weber number, ρ and σ the density and surface tension of the liquid, V and d are the velocity and diameter of the droplet [25]. The Weber number is a good indicator of droplet bouncing pattern, as far as the water-air interface is not disrupted and the impact and retracting of the droplet remained normal throughout the flow [26]. In the non-wetting regime, the liquid droplet remains on the surface when the We_d is low because of viscous dissipation from expansion and retraction which results to insufficient kinetic

energy for liquid droplet rebound. A complete rebound is observed when the We_d is intermediate, and the liquid droplet shatter We_d when becomes very high.

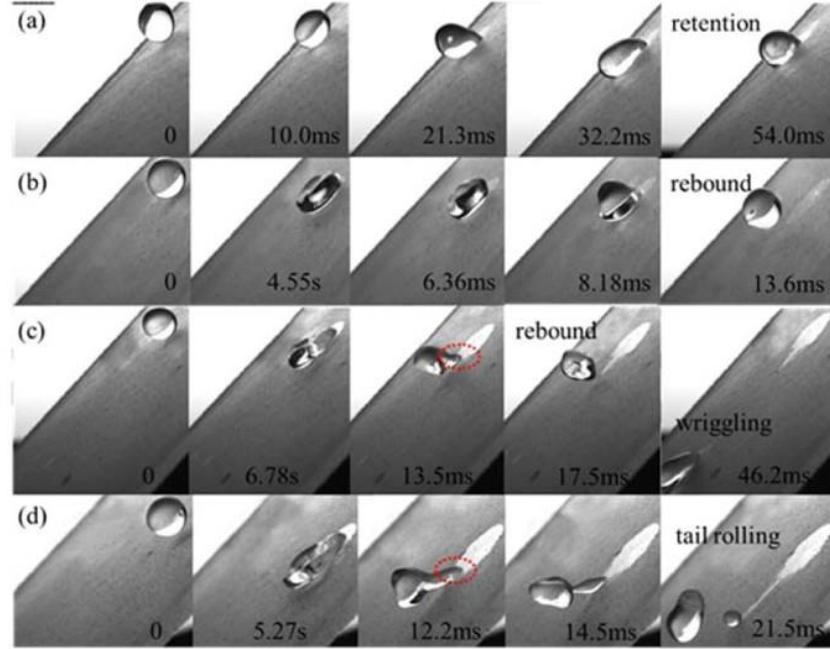


Figure 1.5: Removal processes of ERMs on HSs by droplet impinging under different We_N : (a) retention, $We_N = 1.14$, (b) rebound, $We_N = 2.67$, (c) rebound-wriggling, $We_N = 8.39$, (d) rebound-tail rolling, $We_N = 16.8$ [23].

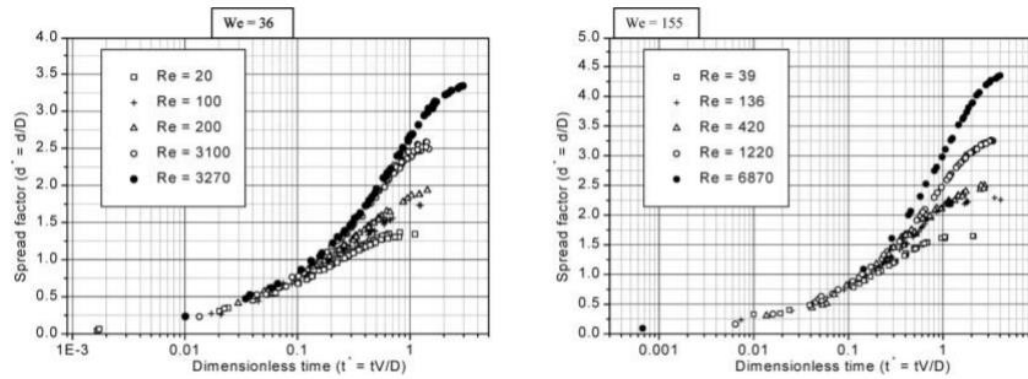


Figure 1.6: Influence of Reynolds number on the spread factor; the Weber number is kept constant ($We=36$, left; $We=155$, right) [25].

At constant Weber, increasing in Reynolds number leads to higher spreading diameter. Even though Weber and Reynolds are very close, the liquid drop shows are a clear distinction in separation factor $t^* > 1$. The difference in the spreading factor has not resulted from the wettability effect since all the experiments are carried out using the same surface [25].

Rolling and sliding droplets

The pickup of the dust particles is mainly due to the adhesion of the dust particle to the water-air interface which is greater than the adhesion of the dust particles to the superhydrophobic surface. The dust property also plays significant rolling in the cleaning process. When the water droplet completely wet the dust, there is a transition of the particles from the interface to inside the water droplet. on the other hand, for hydrophobic particles such as epoxy resin microsphere (ERM) the transition from the water-air interface to the inner part of the droplet becomes difficult. Therefore, the ERM particles stay on the interface while the liquid is moving [27].

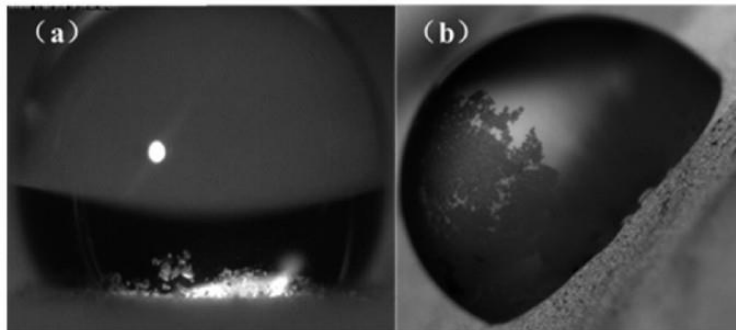


Figure 1.7: (a) Dust particles sink to the bottom of the droplet, (b) ERM particles adhere to the surface of the droplet forming a liquid marble [27].

Introducing dust particle on the hydrophobic surface increase the pinning of the liquid droplet thereby reducing the translational and rotational velocities as shown in Figure 1.8. This phenomenon changes the wetting diameter of the liquid droplet during the dust cleaning process. The wobbling nature of droplet motion also influences the dust cleaning due to the striation-like pattern created in the path of the droplet. In addition, the ratio of the cleaning area by the projected area for rolling/sliding droplet is determined for two droplet volumes (20 μ L & 60 μ L) and two inclination angles. By increasing the plane inclination angle, the droplet wobbling reduces while the acceleration of the droplet down the inclined surface is enhanced. This reduced the striation-like pattern effect on the path of the droplet, thereby maximizing the portion of the projected area being cleaned by the water droplet as shown in Figure 1.9 [15].

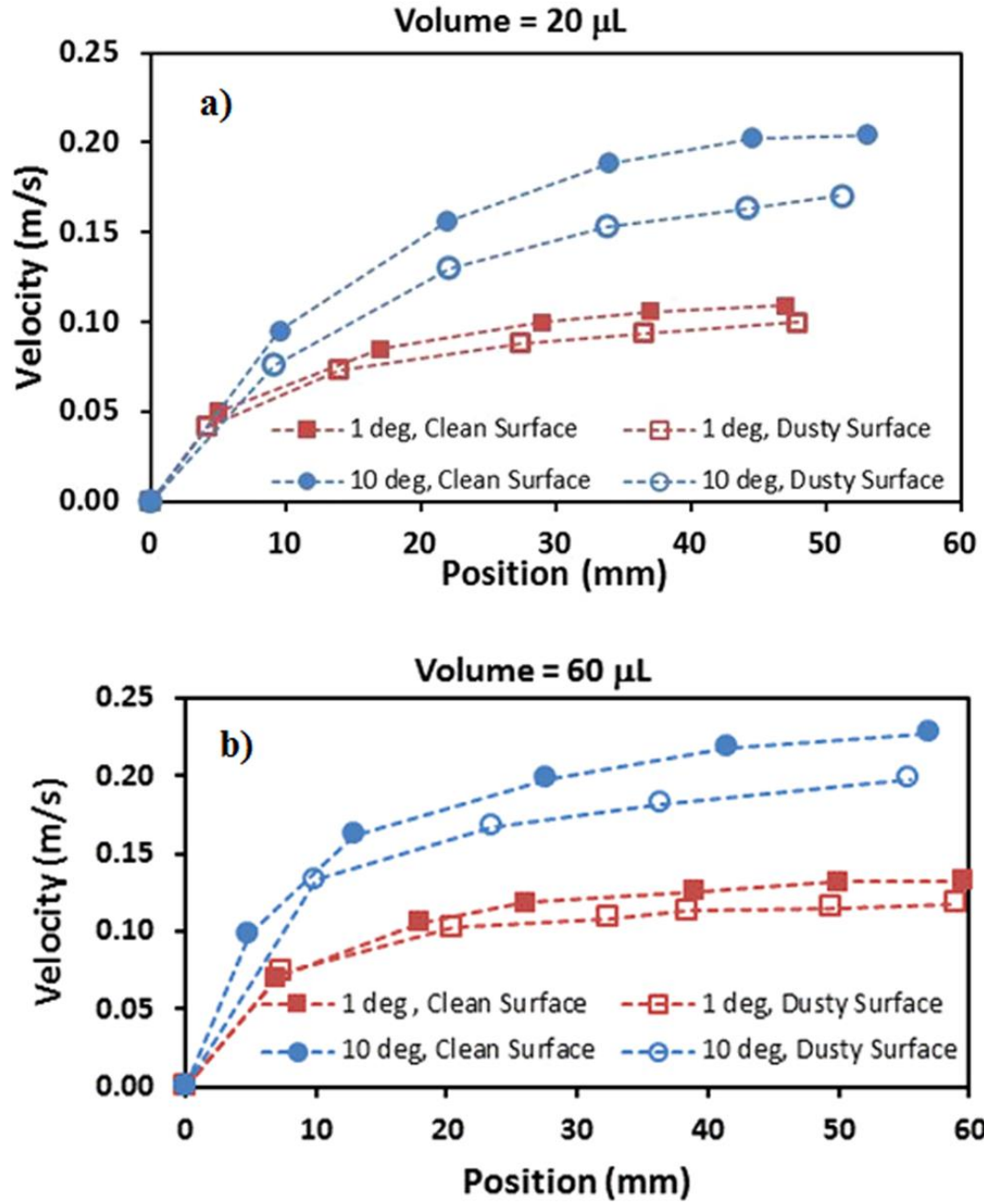


Figure 1.8: Droplet translational velocity with and without dust particles on the surface for two inclination angles: (a) droplet volume is 20 μL , and (b) droplet volume is 60 μL .

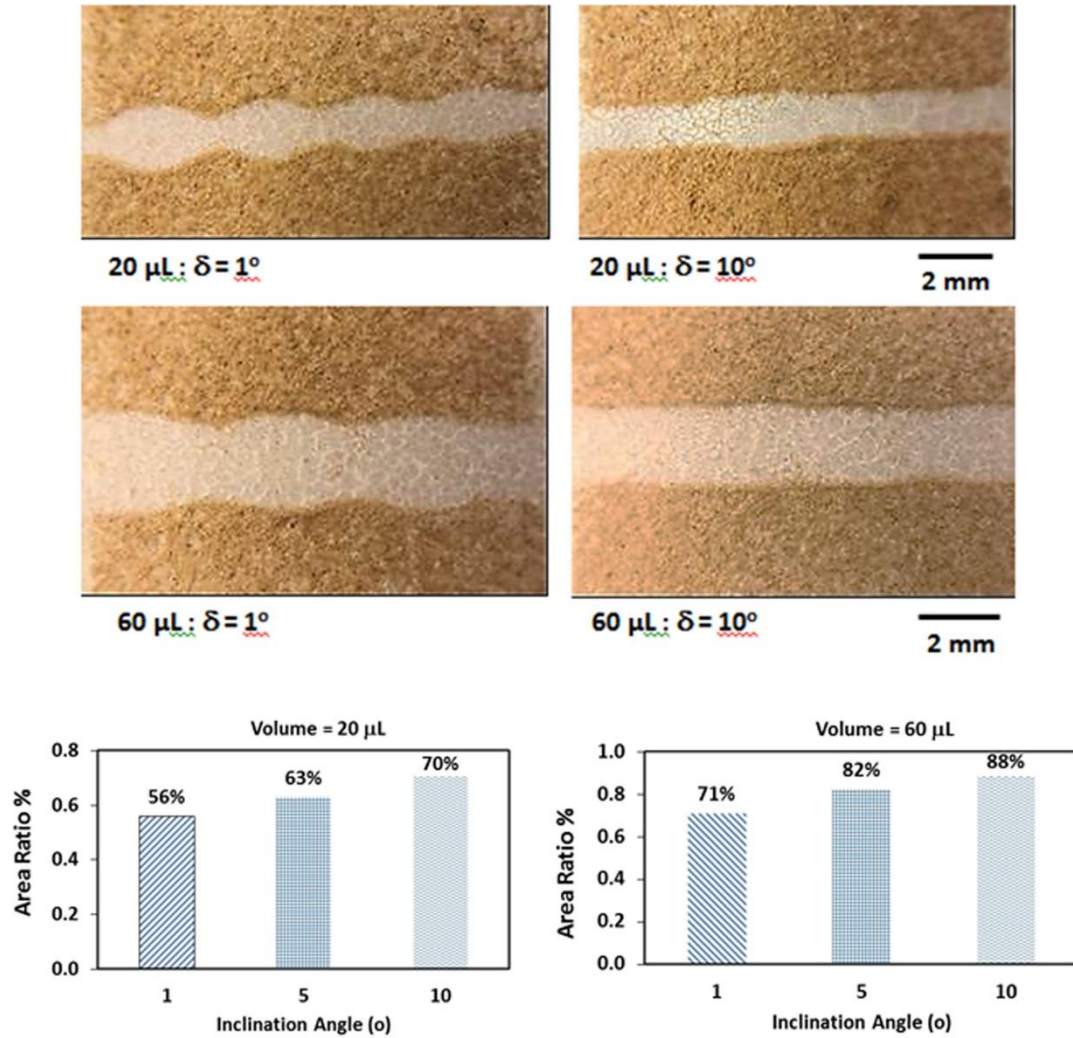


Figure 1.9: Optical image of a droplet path on a hydrophobic surface with the presence of dust particles for two droplet size and two inclination angles. The ratio of area cleaned by droplet over the projected area (maximum wetting width $\times$ Sweeping length) is also shown for various inclination angles and two droplet volumes.

The dust cleaning enhancement by the rolling and sliding droplet is more apparent for larger size liquid droplet. An increase in the droplet acceleration results into a rise in the rotational bond number, and therefore a higher rotational bond number results in a more stable wetting diameter, thereby enhancing the Dust cleaning process.

1.3 Research Objectives

The efficiency of solar energy collecting devices largely depends on the quantity of solar irradiant energy received by the active surfaces of such devices. However, accumulation of dust particles on such surface attenuates the overall performance of such systems, hence, there is a need to get the active surfaces clean, through minimum energy and material consumption. For dust cleaning applications, droplet rolling, sliding and spinning becomes critical as a substantial amount of dust can be removed if the surface wetting state is hydrophobic, Therefore, the main objectives of this research work include the followings:

- i. Develop superhydrophobic surfaces through solution crystallization with acetone and a dip-coating method.
- ii. Assessment of surface characteristics; surface energy measurement, surface texture analysis (SEM, optical 3D, AFM) and transmittance
- iii. Develop a mathematical model that predicts the effect of droplet size, wedge and inclination angles on droplet motion on a superhydrophobic wedged channel.
- iv. Experiment on droplet study using a high-speed camera and post-process the result of droplet dynamics using image and video processing tools.
- v. Use numerical code (Conservative level set) to model the droplet dynamics on superhydrophobic surfaces.
- vi. Investigate the dynamic (rolling, sliding and spinning) motion of water droplet due to differences in surface energy for the two surfaces that form the wedge channel.

1.4 Significance of the study

Solar irradiance and module cell temperature are the two major factors that affect the performance of solar PV panel [28]. Dust particles are generated from many sources such as air pollution, volcanic eruptions, pedestrian and vehicular movement, wind forces among other factors [29]. Dust particles deposition overtime results in fouling effect, and the amount of dust deposit daily creates a partial or complete shadow on the module cell, which affect the PV performance [6]. Hydrophobic coating of PV surfaces provides the self-cleaning condition, thereby making such surfaces non-wettable to water droplets. Water droplet motion on the hydrophobized dusty surfaces creates a track of the clean path. However, droplet spinning during rolling is expected to improve droplet path on hydrophobic surfaces, such as parallel path edges can be achieved.

1.5 Scope and limitations

Scope

The scope of the work has multifold and they are listed below:

- i. Develop superhydrophobic surfaces of different surface roughness using acetone solution crystallization and dip-coating technique.
- ii. Investigate the dynamics of a water droplet on wedge channel experimentally using a high-speed camera.

- iii. Develop an analytical model to predict the effects of wedge angle, inclination angles and droplet volume on droplet rolling, sliding and spinning motion down an inclined superhydrophobic wedge channel.
- iv. Use numerical code to simulate the dynamics of the water droplet on the inclined hydrophobic wedged channel.
- v. Investigate the possibility of creating spinning motion within the water droplet using the numerical results.

Limitations

- i. Experimental data rely on high-speed camera records. Small changes in focusing limits the correct recording. Hence, care is taken to minimize this effect.
- ii. Wetting state changes slightly on the hydrophobized surface. This influence droplet behavior on the surface. Hence care is taken to minimize this effect.
- iii. Conservative level set method is the only numerical method adopted in the study. However, experimental data has provided a means of validation and calibration of the numerical model. |

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CHAPTER 2

LITERATURE REVIEW

A considerable number of researches has been conducted to explore the effect of dust fouling on solar energy collection devices, and the various methods of removing or preventing dust settlement are reported. Various analytical models were developed to predict sliding, rolling and impacting of a liquid droplet on a hydrophobic and hydrophilic surface. Different techniques are used to alter the surface property for hydrophobic or hydrophilic nature, depending on the application. Several numerical algorithms that solve 2D and 3D multiphase flow problems are reported.

2.1 Dust fouling effect

Studies about the influence of dust fouling on the performance of Photovoltaic (PV) panels have been extensively studied in previous works. Most of the studies indicate a very large reduction in PV glass optimal transmittance with the accumulation of dust. For instance, Said and Walwil found that the transmittance reduces by 20% when exposed to dust storm for 45 days at 26° (Latitude of Dhahran) inclination, with an average dust accumulation of 5g/m^3 [6]. In other to investigate the effect of tilt angle, Jiang et al. Studied airborne dust deposit on PV performance for different tilt angles, exposure period, site climate conditions, wind movement and dust properties. The result shows that 0 – 26% of the PV performance is loss by increasing the dust deposition rate from 0 – 26 g/m^2 . The exact value of how efficiency is reduced was not investigated for different cells [30]. Mohamed

and Hasan investigated the effect of dust accumulation and frequency of cleaning for optimum PV performance in Libya and other desert climates. Discovered that weekly water cleaning of the PV module during the dustiest period (February to May) can save 97.5 – 98% of PV efficiency [31].

Ghazi et al. analyses various innovative techniques developed and findings from various researches towards mitigation of dust effect on the flat surfaces for different regions and climates of the world. Findings reveal that the Middle East and North Africa have the highest dust accumulation history over all regions of the world. Recommendations for cleaning mechanisms and methods are highlighted for the benefit of commercial institutions [32]. Ibrahim developed empirical relations that predict dust accumulation over time, open-circuit voltage and short circuit current; given as $I_{sc} = -5.5612t + 211.85$, $V_{oc} = -0.0192t + 2.2$. An average reduction of 2.78% and 0.863% per day were obtained for short circuit current and open circuit voltage [33]. Mekhilef et al. found that low humidity level in the air enhances wind speed which increases the cooling of PV and in turn leads to better efficiency. However, wind speed facilitates the lifting, shading and deposition of dust on PV surfaces which results in poor performance [34]. Sarver et al. reported that frequency of more dew than rainfall especially in the temperate and tropical climate leads to more severe soiling situation due to cementation of dust with little moisture. Over the five decades of study, it is reported that the amount of solar radiation can typically be in the range of 20 – 50% for moderate dusty conditions. However, with dust cementation 100% losses have been realized. From the 1970s to 1990s more attention is paid to physical cleaning using water and detergent while recent studies are focused on active systems (dust driven techniques) and passive systems (self-

cleaning/superhydrophobic surfaces). Some of the suggestions for future work are; Devising methods that accurately determined the thickness of dusty layers. Determination of adhesion of dust to surfaces. Establishing a relationship between atmospheric dust and deposition rate on exposed surfaces. While modelling for dust mitigation and prevention approaches for details should be included about surface properties, orientation, wind speed, direction and turbulence. It is recommended for sensor monitoring for information on the local concentration of dust [29].

Hegazy Studied the effect of dust accumulation on the performance of PV collector for different exposure durations, tilt angles and climatic condition in Egypt. An empirical relation of accuracy $\pm 6\%$ developed which allows for the determination of the performance of PV under different tilt angles, climates and duration of time [30]. El-Shobokshy and Hussein Studied the effect of 5 different kinds of dust (three of which were limestones particulate and 2 were carbon particulate) on PV cell performance. The study was conducted for various dust sizes and at different deposition densities. Dust with finer grains such as cement was found to adversely affect the cell more than coarse grains. Carbon particulates such as soot and other product of combustion are found to have the highest negative effect on PV performance [35]. Mastekbayeva and Kumar. Presented the effect of dust on the transmittance of 0.2 mm thick polyethene (LDPE) glazing commonly used in solar space heating in tropical climates. An empirical relation between transmittance reduction and deposition density was generated for Bangkok clay (53 - 75 μm , size). The inclination of LDPE glazing by 15° in a tropical climate has a dust accumulation of 3.72 g/m² that reduced the transmittance from 88% to 76% [36]. Rahman et al. studied the effect of environmental dust on the performance of PV panel in Bangladesh. A micro-controller

based system was designed and implemented for dust cleaning purpose. It was reported that the accumulation of dust on a PV panel exposed for one month has reduced the efficiency by 35%. The designed controller was found to improve the efficiency of the PV panel while requiring no external energy [37].

Environmental conditions such as humidity, wind speed and dust accumulation have a direct effect on the performance of PV cells. A study made in two approaches to investigate environmental effects; First, involved determination of the effect of an individual factor on performance. Second, study the inter-relations among these factors. The low humidity level in the air enhances wind speed which increases the cooling of PV and in turn, leads to better efficiency. However, wind speed facilitates the lifting, shading and deposition of dust on PV surfaces which results in poor performance [34]. Adinoyi and Said studied the effect of dust deposit on the performance of the PV module in the Eastern province of Saudi Arabia. They reported that about 50% of the PV output power is lost when exposed to an atmospheric environment for an average period of 6 months. It is discovered that tracker incorporated PV modules despite having improved efficiency, also 50% of dust accumulation is reduced [38]. Sayyah et al. presented a review on the effect of dust accumulation on the energy yield of solar energy harvesting devices with emphasis on a flat plate PV system. The parameters under study include; type of collectors, location, climate type and exposure period. Dust size, chemical composition, and accumulation are closely related to the energy yield of PV flat plate. Particles with high light absorption property such as soot and Iron oxides, as well as very fine particles ($0.2 - 2.0 \mu\text{m}$) greatly affect PV energy yield [39].

Touati et al. investigated the sensitivity of two solar PV module types to dust, temperature, and relative humidity for Doha, Eastern province of Saudi Arabia. The two PV modules under study are monocrystalline and amorphous solar cells with efficiencies 85% and 70% respectively. Reported that dust accumulation decreases the power output of the PV modules by 10% in 100 days. For temperature over 40°C and relative humidity over 22% (typical of Duha climate) the performance of Amorphous PV module is affected more than monocrystalline, hence it is recommended that monocrystalline show to used in Doha [40]. Feuermann and Zemel studied the effect of dust on the degradation of pyranometer accuracy. Under arid climatic condition typical of Israel, the sensitivity of pyranometer reduces by one permille per day [41]. Elminir et al. studied the dust transmitting surfaces for different tilt and azimuth angle for seven months. Using 100 glass sample, it is reported that reduction in the normal transmittance largely depends on tilt angles and orientation of surface in the prevailing wind direction. It is also reported that for two glass with dust deposit of 15.84 g/m² and 4.48 g/m², there is a reduction in transmittance by 52.54% and 12.38% respectively [42]. Rajput and Sudhakar studied using electric power output, the effect of dust on the performance of the PV panel. They reported that dust accumulation reduces panel efficiency by 89% and power output by 92.11% [43]. Qasem et al. Simulated the effect of dust accumulation and tilt angle on the performance^{oo} Cadmium telluride PV module using PSPICE model. It is reported that the performance of the PV module reduces continuously and efficiency can be reduced by 34% with 90days. The tilt angle is varied over time and change which has a significant effect of dust accumulation. Hot-spot formation is realized for a tilt of zero degrees [44]. Sayyah et al. reviewed various approaches for mitigating the soiling effect of dust on concentrating PV and concentrating

solar collectors. Reported some mitigation method that includes natural cleaning by rain and snow, mechanical or manual cleaning by water and detergent, as well as autonomous cleaning using electrodynamic screen (EDS) on which dust particles are charged and drive with electrostatic force [45]. Wang et al. investigated the performance of Fluoride and Silicon base super-hydrophobic films in mitigation of dust accumulation on PV modules. While simulating using constant atmospheric temperature and humidity with 25 μ m red soil particles to represent the actual condensation process, the influence of dust on PV coated with Fluorine super-hydrophobic film is less than that of the Silicon coated [46]. Lu et al. used SST k- ω turbulence model with UDF inlet profile while employing the discrete particle model (DPM) to simulate the mechanism of dust particles deposition on solar PV panel mounted on an isolated building. They investigated the effect of dust particle sizes, quantities of dust released, and the effect of gravity on dust deposition rate. Reported that the CFD for the wind flow profile are in good agreement with experimental results reported in literatures. It was found that effect of gravity is highly significant in large particles. This could reach 75% for 50 μ m dust and 5% for 5 μ m dust. It was discovered that the deposition rate rises and fall while increasing particle size. The effect of varying quantity was found to be 8% significance [47].

Table 2.1: Summary of some research outcomes on dust fouling effect

Authors	Study & location	Duration	Dust effect
Said and Walwil [6]	KSA	45 days	The glass transmittance is reduce by 20% when exposed for 45 days at latitude of Dhahran (26°N)
Mohammed and Hassan [31]	Libya	4 months	Weekly cleaning can save efficiency by 98% during most dusty period
Ibrahim et al. [33]	Egypt	10 days	V_{oc} decreased by 9% and I_{sc} by 27% after 10 days
Rahman et al. [37]	Bangladesh	1 month	Dust accumulation reduce performance by 35%
Adinoyi, et al. [38]	KSA	6 months	The output power decreases by 50% during six months of outdoor exposure
Touati et al. [40]	Qatar	100 days	The efficiency decreased by around 10% after 100 days of dust accumulation
Elminir et al. [42]	Egypt	1 month	The solar module output power decreased about 17.4% per month
Rajput et al. [43]	India	Not reported	The efficiency of 6.38% for clean modules for dusty modules
Qasem et al. [44]	Kuwait	3 month	PV efficiency is reduced by 34% in 90 days

2.2 Hydrophobic and hydrophilic materials

Song et al. studied water droplet on hydrophobic lined-patterned surfaces. Retention force on hydrophobic surfaces decreased by decreasing silane with ratio. Sliding acceleration was governed by surface chemical composition as the patterning structure [48]. Scheider et al. studied the effect of viscous drop on superhydrophobic surfaces due to magnetic gradient. The chain orientation of paramagnetic particles accounted for viscosity increment in order to sustain the droplet movement [49]. Drelich et al. reviewed hydrophilic and superhydrophobic materials and surfaces. Introduced the physics behind hydrophilic phenomenon with recommendation on how to define superhydrophilic surfaces and coatings [50]. Al-Sharafi et al. investigated internal fluidity of sessile droplet on both hydrophilic and hydrophobic surfaces. The counter circulating cells were formed in the droplet on the hydrophilic surface and their behavior in the flow field was as a result of Marangoni and buoyancy force effect [51].

2.3 Droplet interfacial energy

Retention force has a direct effect on contact angle hysteresis, and droplet shape. Extrand and Kumagai study the relationship between contact angles, retention energy and droplet shape on an inclined surface using water and ethylene glycol as liquids and four polymers and silicon wafers as substrates. Depending on liquids and substrate, hysteresis ranges from 9 to 66°. A linear correlation exists between the droplet aspect ratio and contact angle hysteresis. Retention force increases linearly with droplet elongation [52]. Meiron et al. studied the effect of droplet volume, vibration time, frequency and amplitude in the

determination contact angle of the droplet on a rough vibrating surface. The apparent contact angle turns out to be practically identical with the measure values using Wenzel equation [53]. Tadmor studied droplet volume and the three interfacial energies. presented the relationship between advancing, receding as well as young contact angles as given in Eq. (2.1)[54].

$$\frac{dL}{dA_p} = \left(\frac{\pi 2 - 3 \cos \theta + \cos^3 \theta}{3 V \sin^3 \theta} \right)^{1/3} \quad (2.1)$$

where L and A_p are the circumference and area of the planar interface, V and θ are the droplet volume and contact angle.

Elsherbini and Jacobi studied the relationship between droplet geometric parameters and retention force for a droplet at the verge of sliding on an inclined surface. Two circles method was adopted to predict the maximum size of the droplet as shown in Figure 2.1. This scheme helps to accurately determine the droplet volume and contact area for calculation of retention force.

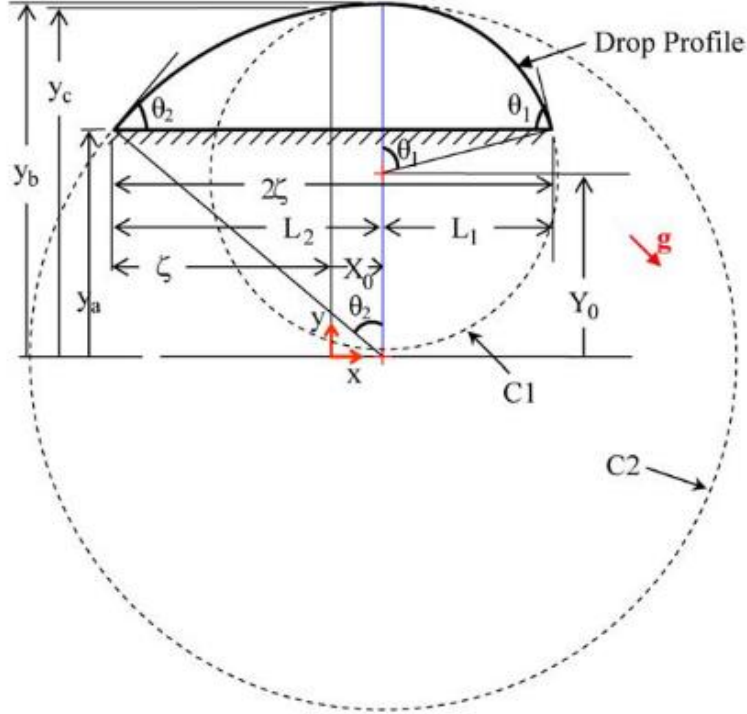


Figure 2.1: The profile of a drop on an inclined plane with nomenclature for the two-circle method [55]

The retention force is greatly affected by the aspect ratio of droplet contour [55]. Bormashenko and Whyman analyzed the effect of line-tension in stabilizing the cassie-like wetting in hydrophobic nanoscaled reliefs. Despite the line-tension was assumed to have negligible effect. However, it greatly contributes to the stability of cassie wetting state [56]. Kim et al. analyzed adhesion of the water droplet placed on a plane surface. they formulated a model that predicts the surface adhesion energy of a water droplet on plane surfaces

$$E''_{Adhesion} = \frac{F_x \times Y_{COM}}{A_{wet}} \quad (2.2)$$

where F_x is the summation of all forces along the inclination plane, Y_{COM} is the position of the center of mass, A_{wet} is the wetted area. They discovered that irrespective of the droplet

volume, the energy per unit contact area remains constant [57]. Balu et al. Studied directional Mobility and Adhesion of Water Drops on Patterned Superhydrophobic Surfaces [58].

2.4 Mechanics of droplet motion

Annapragada et al. analyzed droplet dynamics on an inclined surface. They developed a model for the dynamics of droplet down an inclined surface. Surface property affects droplet pinning and roll-off [59]. Liquid droplet motion on the lubricant-impregnated surface has a different contact line dynamics to clean surfaces. Morphology of the contact line consisting of a finite annular ridge of lubricant above the surface texture which governs the contact line pinning that regulates the droplet initial resistance to motion as well as control the level of viscous dissipation as the droplet begins to move [60]. Viscous dissipation is also affected by localizing droplet heating. Therefore, Al-Sharafi et al. investigated the influence of thermal capillary and buoyant forces on flow characteristics in a droplet on a hydrophobic surface due to localized heating. It was discovered that a combination of Marangoni and buoyancy forces generate circulation current within the liquid droplet. Nusselt number of the internal flow increases with increase in contact angles 1.e. 110° - 150° [61]. Al-Sharafi et al. simulated the effect of thermal capillary and buoyancy forces of a droplet on hydrophobic surfaces. The flow pattern within the droplet is highly sensitive to change in droplet-surface contact angle under thermal load [62]. Yilbas et al. studied the effect of plane inclination angle and droplet size on the droplet dynamics. Considering the balance of forces they modelled the droplet rotational speed relation.

$$\omega \tag{2.3}$$

$$= \sqrt{\frac{5}{2mR} \left(mg \sin \delta - \frac{24}{\pi^3} \sigma f(\cos \theta_R - \cos \theta_A) - \mu A_w \frac{\partial u}{\partial y} - \frac{1}{2} C_d \rho_a A_c U_T^2 \right)}$$

Rotational speed varies directly with the inclination and inversely with volume. In the rolling regime, the resultant force at the contact interface changes continuously which accounted for the wobbling [63].

2.5 Rolling and Sliding droplets

Furmidge studied the effect of droplet size, inclination angle and nature of the surface on the sliding of liquid drops for spray retention purpose. The proposed theory of spray retent agreed well with the experimental result.

$$R = k \left(\frac{\pi \gamma_{AL} (\cos \theta_R - \cos \theta_A)}{24 \rho g \sin \alpha} \right)^{1/2} \cdot \left(\frac{(1 - \cos \theta_A)^2 (2 + \cos \theta_A)}{\sin^3 \theta_A} \right)^{1/2} \tag{2.4}$$

This expression relates spray retention in terms of the physical properties of the bulk liquid and solid surface involved. Little modification was made to account for deviations observed with easily wetted surfaces [64]. The infinitesimal volume of a water droplet on superhydrophobic substrates possess dynamical motion similar to a ball on flat surfaces. Hopkins and Patterson analyzed the effect of spinning and rolling speeds on the path of a bowling ball. They developed ordinary differential equations and solved the equations in closed form. The path of ball motion reveals a parabolic shape to a certain characteristics

time and continued in a straight path without slipping [64]. Miwa et al. studied the effect of surface roughness on rolling droplet on an inclined surface. They came up with a model that captured the effect of sliding and contact angle for the droplet moving on a hydrophobic surface

$$\sin \alpha = \frac{2rk \sin \theta' (\cos \theta' + 1)}{g(r \cos \theta + 1)} \left\{ \frac{3\pi^2}{m^2 \rho (2 - 3 \cos \theta' + \cos^3 \theta')} \right\}^{1/3} \quad (2.5)$$

Eq. (2.5) describe the relationship between contact angle (θ') and sliding angle (α) [17]. Frohlich investigated the factors that influence the hooking of the bowling ball. Numerical simulations show that variable friction along the lane on which the ball moves greatly influences the ball's trajectory [65].

Rios et al. studied the effect of nanostructure, chemical composition and droplet size on contact and sliding angles. They reported that, for any measured contact angle, the sliding angle of the water droplet on a smooth and nanometric roughed surface can be predicted using the developed model. For various droplet sizes and roughed surfaces, the relation between contact and sliding angles show good agreement with the analytical model [18]. Sakai et al. studied the effect of droplet mass on rolling and sliding movements. Sliding acceleration highly influenced the rolling motion of water droplet, whereas for small droplets sliding acceleration occurred mainly with sliding mechanism [19]. Suzuki et al. studied the rolling & slipping motion of water droplet between fluoroalkyl silane coated parallel plates. They reported that rolling motion is predominant for the acceleration of water droplet motion [66]. Sakai et al. investigated internal fluidity of sliding water droplet

down an inclined hydrophobic plane. On superhydrophobic surfaces, slipping dominates the droplet acceleration. whereas, during sliding on the hydrophobic surface, both slipping and rolling governed the flow speed [20]. Hsieh et al. studied the sliding nature of oil droplet down a textured surface. Sliding nature of water droplet is governed by plane inclination angle as well as adhesion force at the droplet-surface contact [21]. Thampi et al. simulated the rolling and sliding of water droplet off an inclined surface. They reported that rolling motion of droplet is dominant when the droplet approaches circular shape and when the difference in viscosity between the water droplet and the ambient fluid comes larger [67]. Nikajima et al. studied triangle hydrophilic region with the sliding of a water droplet on a hydrophobic surface. It was discovered that, with the proper design of shape and alignment of chemical heterogeneity, it is possible to control the sliding velocity maintaining static contact angle [68]. Sutha et al. analyzed ZnO nail bed surface morphology under the roll-off of a water droplet. They formulated a model of the relationship between topographical and physical parameters (volume, mass and surface tension) [69]. Yakubov et al. studied suspended particles dynamics in rolling-sliding contact. When the particle diameter is less than the film thickness i.e elastohydrodynamic regime, the particles were observed to behave as a continuum [70].

2.6 Numerical algorithms for multiphase flow problems

Numerical investigation of droplet rolling, sliding and spinning behavior on the hydrophobic surfaces remains important for predicting the dynamics of droplet behavior motion down the inclined PV surface. Shikhmurzaev proposed a model for the advancing

contact line motion of fluid on a flat solid surface. The model is given in dimensionless form in Eq. (2.6)

$$P^s = \lambda(\rho^s - 1) \quad (2.6)$$

where P^s is determined by the material of the three contact media (i.e. Solid, liquid and gas), ρ^s is a function of liquid gas pair, λ is a function of the dynamic contact angle. The motion of the fluid creates a surface tension gradient that drives the flow. In the case of low Reynold and capillary number, the surface tension gradient determines the contact force at the fluid and solid interface which affects the contact angle. The dynamic contact angle and the tangential force that depends on the motion of the contact line were successfully determined. Described the fluid motion as rolling as observed in an experimental investigation. Relationship between limiting dynamic contact angle and the parameters in the youngs' equation were determined and a method for obtaining these parameters is proposed. The method was tested for a smooth surface and compared with both experimental and conventional numerical method developed on the rough surface [71].

Osher and Sethian first devised the algorithm known as the *propagating with curve-dependent speed* (PCS) based on Hamilton-Jacobi formulations. The algorithm is an approximation of the equations of motion using the technique in hyperbolic conservation laws. The equation resembles the Hamilton-Jacobi equations with a parabolic right-hand-side. The algorithm provided a solution that accurately captured sharp gradient and cusps moving fronts. The method is predicted to be applied in more general Hamilton-Jacobi related problems [72]. The method was modified by Sussman et al. and named The *Level*

set approach as a solution to incompressible two-phase flow with sharp interfaces [73]. The interface has a zero level set of a smooth function. The level set method adopted the second-order projection method for differentiating the convective terms in the momentum equation. The new treatment of level set method was able to solve problems with large density and viscosity ratios as well as surface tension for a sharp interface such as the motion of air bubbles in water and water droplet in air. The level set method has not predicted a momentum-energy coupled problem with much accuracy. This is due to mass loss which has not been accounted for in the mass conversation equation. Therefore,

Sussman et al. presented an *adaptive level set approach* which also provides a solution to incompressible two-phase flow. in this work, the Level set scheme was coupled to an adaptive projection method for the incompressible Navier-stokes equation. This technique helps in achieving a smooth gradient of density, viscosity and level set function at the free interface. 2 dimensional axisymmetric and 3-dimensional results of motion of air bubbles in water and water droplet in the air were computed with better accuracy. The algorithm cannot handle problems will irregular geometries, heat and vaporization, applicable to thermal inkjet devices where bubble aid flow out of inkjet [74]. In order to have a better prediction of surface tension and interfacial topology, Sussman and Puckett couple the level set to volume of fluid method and obtained a *coupled Level set/ Volume of fluid method* to solve a 3-dimensional axisymmetric two-phase flow problem. A direct comparison was made with the results from Level set method, Volume of fluid method and the boundary integral method. Computational examples were basically featuring surface tension and changes in the topology of the flow. The coupled Level set and Volume of fluid (CLSVOF) method was tested for 2-dimensional, axisymmetry, and fully 3-dimensional

problems and found to be similar or even better in featuring surface tension and flow topology than the compared methods [75]. Sussman and Hussaini developed a *discontinuous spectral element method for the Level set equation*. This is due to the increased popularity of the existing Level set method as a solution to many fluid dynamics problems. Exponential convergence was demonstrated for both interfacial advection and reinitialization step. The order of accuracy of the developed method was higher than most finite element and finite difference methods. However, solutions for a sharp corner in the zero level set did not match with the results obtained from Front-tracking methods, particle methods, or hybrid particle method [76].

Jacqmin developed the *phase-field method* as a solution for Navier-stokes equation in two phase flow. Calculations were performed for break ups on line flow and the breaking wave in sloshing flow. the phase field is shown to be energetically and thermodynamically consistent method and can be able to handle long time computations with repeated interface break ups and coalescence [77]. Moreover, the Phase-field method can also be used to predict the dynamics of a rolling droplet. The main problem with the Phase-field is the convergence difficulties often encountered when solving the 4th-order Cahn-Hilliard equation and loss in mass associated with the reduction of this equation to 2nd order [78]. Takada et al. proposed the *NS-PFM method*, a computational method by combining Navier-stoke (NS) equation and Phase field model (PFM) based on free energy theory. It is reported that the model has a good prediction for the motion of immiscible, incompressible, two-phase, isothermal flows with high-density gradient such as water-air system simply without using the convectional interface tracking algorithms. In the proposed method, the problem with numerical diffusions and oscillations as well as

interface restructuring are resolved. The model predicts pressure changes due to surface tension. An example of liquid falling through stagnant air to a given liquid film was successfully simulated in 3 dimensions [78].

The numerical method incorporating the volume-of-fluid (VOF) with the smooth function can also predict the dynamics of the droplet rolling onto the hydrophobic surfaces. However, the numerical artificial viscous dissipation created generates the parasitic currents in the droplet fluid which has an effect on the deformation of the droplet [79].

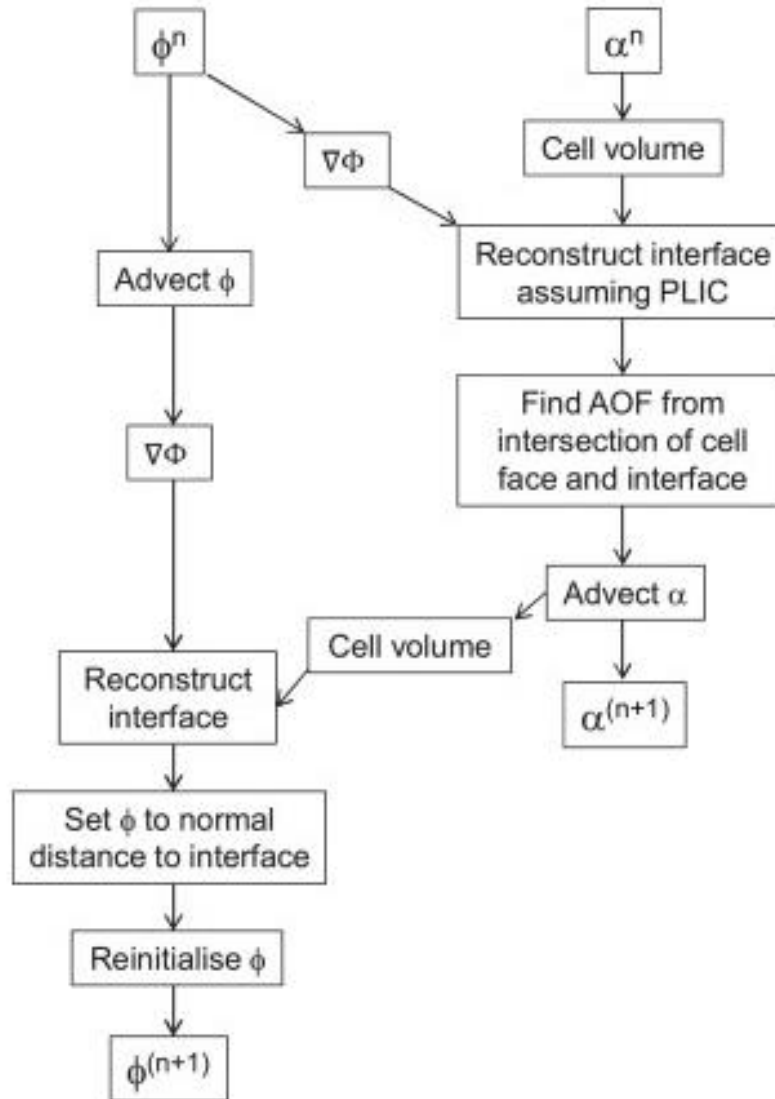


Figure 2.2: Overview of capturing algorithm use to update VOF, α , and Level set ϕ [25]

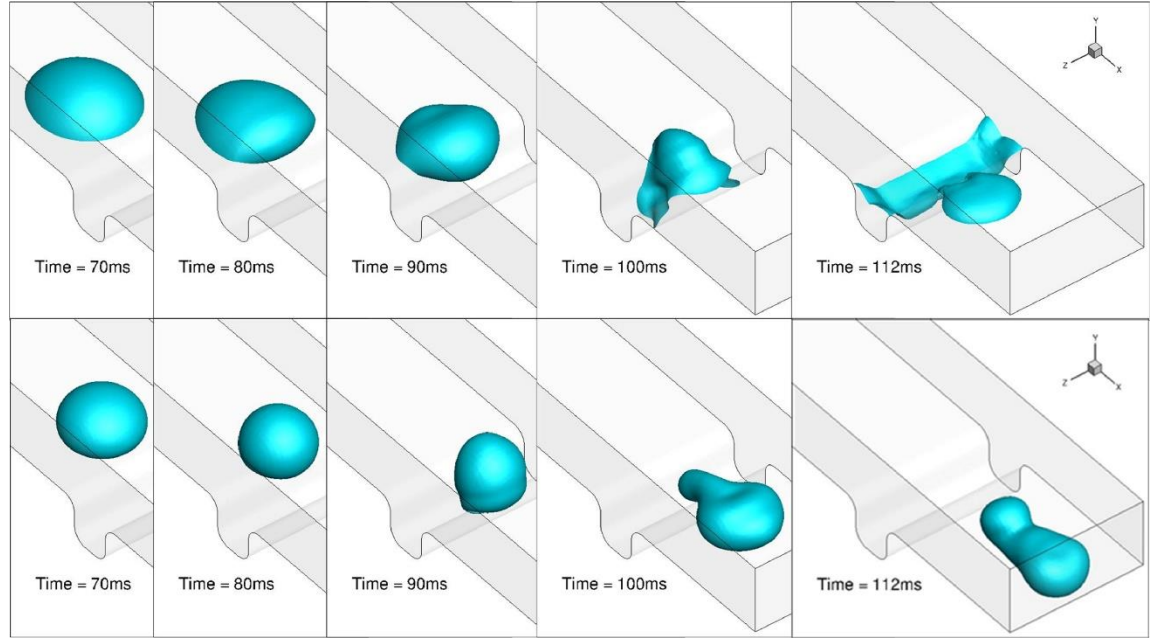


Figure 2.3: CLSVOF simulations of water droplet flowing across a channel with curved corners:
top, hydrophilic surface; bottom, hydrophobic surface [80].

The numerical model coupling the level set and volume of fraction (CLSVOF) methods, as well as smooth particle hydrodynamics, predicts realistic rolling droplet behavior on the hydrophobic surfaces [81]. This tool was used to investigate the exterior water management of road vehicles as shown in Figure 2.3. The tool can accurately simulate the surface flow of droplet on complex geometries for different surface properties [80]

Osher and Fedkiw presented an overview of recent developments in the *Level set method*. The level set method is a simple and versatile method for modelling interfacial motion in 2D and 3D space. The study focused on the variants and extension of new methods such as dynamic surface tension method, the fast method for steady-state problems, and the variant level set method. Applications of level set method to 2D and 3D problem are

reported. Such applications include; Kinetic crystal growth, Stefan's problem involving melting of ice and freezing of water, epitaxial growth of thin through molecular beam epitaxy (a method for developing an extremely thin layer of a film by atomic deposits on a substrate in a vacuum), computer vision and image processing application [82]. Sussman and Hussaini developed a *discontinuous spectral element method for the Level set equation*. This is due to the increased popularity of the existing Level set method as a solution to many fluid dynamics problems. Exponential convergence was demonstrated for both interfacial advection and reinitialization step. The order of accuracy of the developed method was higher than most finite element and finite difference methods. However, solutions for a sharp corner in the zero level set did not match with the results obtained from Front-tracking methods, particle methods, or hybrid particle method [76]. Van der Pijl presents a mass conserving *level set method* to study bubbly flow. Attention was given to mass conservation and integrity of the bubble/droplet interface with regards to change in density, surfaces tension, coalescence. *Volume of fluid* was incorporated into the *Level set method* in order to achieve mass conservation. The combination of Level set method and Volume of fluid has provided an advantage in both the conservation of mass and integrity of the interface. The flow was computed with Marker-and-Cell scheme (pressure correction method). The interface conditions conform to the continuous surface force methodology while the density jump was maintained similar to Ghost fluid method for incompressible flow [83].

Glimm et al. proposed a *conservative front tracking/level set algorithm* that is conservative at all discrete levels including discontinuities and improves the solution from the conventional algorithm by one order of accuracy. It is reported that the proposed algorithm

will provide improved simulation capability [84]. Jemison et al. developed a local piecewise interface reconstruction method for incompressible fluids called the *Coupled Level set and moment of fluid* (CLSMOF) method. In order to determine the gradient and intercept for local reconstruction, they combined the Level set function, Volume of fluid function and reference centroid. Non-linear terms of momentum equation are solved by combining the Sharp interface method developed by Raessi and Pitsch, the collocated grid, variable density and pressure projection algorithm developed by Kwatra et al. Many 2D and 3D simulations were conducted for droplets, bubbles, jets, waves on solid blocks. The resultant method is the novel cell centered projection method for two-phase flow. Mass weighting was used when interpolating for velocity while Inverse mass weighting was used when interpolating for pressure from cell centers to cell faces. For problems related to rising of bubble, co-flowing jet and zero gravity droplet oscillation, MOF, CLSVOF and CLSMOF have comparable results. However, for problems that involve 3D stretching, deforming, splitting, jet impinging, flow through a six holed diesel injector, the CLSMOF maintains the interface with higher fidelity than MOF, CLSVOP and VOP methods. For the single vortex problem, the directional split method (CLSMOF) underperforms by about 30% compared to the unsplit methods. Therefore, future improvement should be done by driving the density directly from volume of fluid function instead of Level set function, so that when a jet of fluid splits into droplets, the droplets will still have an effect on the velocity field [81]. Jadidi et al. presented a *coupled Level set method to Volume of fluid* in an open-source application called OpenFoam in order to solve for two-phase compressible fluid flow problem. OpenFoam provided a good coupling for Level set and Volume of fluid

methods. Surfaces tension force, as well as interface curvature, which are the parameters of interest, are successfully improved in the solution.

Gloth et al. developed an algorithm based on the least square method known as the *Front tracking method* that tracks discontinuities which are integrated with a framework for generalized finite volume solution for conservative laws in an arbitrary element-type unstructured grid. The algorithm handles transport and renormalization of the level set function within a defined range. The front tracking method was demonstrated using some examples of shock wave problems. One-sided extrapolation which defines the local front velocity also provides an update for jump conditions at the front. An error correction term handles topological errors in the tracked front. Special care was taken to develop a level set formation for local topological treatment of fronts. Flux separation concept provides treatment of discontinuity within the finite volume with sufficient accuracy in an arbitrary grid. Although the algorithm was not rigorously conservative, however, results from shock wave problem show that isolated discontinuities can also be treated with a good level of accuracy. Treatment of several and crossing discontinuities are the aims of future work [85]. Nguyen et al. presented a method for solving the hyperbolic system of conservative laws with interfaces called the *discontinuous Galerkin front tracking method*. The interfaces are represented by a number of element boundaries and the interface position is updated using Lagrangian-Eulerian method. interface motion and fluxes are generated from the solution of Rieman problem. A simple re-meshing technique regenerates grid based on distance function in order to maintain the grid quality. In order to handle problems with surface tension, jumps due to surface tension were incorporated in the Rieman solver. B-spine curve was used to compute curvatures at which values of surface tension is evaluated.

The numerical method provides a solution to various Navier-stoke compressible flow systems. The model was reported to have a high level of accuracy in the continuum domain and with little error for discrete mass conservation. The method is in good agreement with the analytical results based on the inviscid linearized theory of Rayleigh. In general, the proposed method can handle material interfaces with surface tension for several geometries [86].

Legay et al. described a method for fluid-structure interaction known as the *Eulerian-Lagrangian method*. The interface between the fluid and the structure phase is defined by a level set function. The liquid phase is treated as a continuum in a Eulerian mesh which the solid structure is treated as discrete in a Lagrangian mesh. The level set method provides a compact framework for writing the weak equation form and for developing and computing the discretized equations. Penalty method and Lagrangian multiplier methods provided the fluid-structure coupling. The fluid phase is discretized by the Eulerian mesh while the solid structure is discretized by the Lagrangian mesh. The two meshes can overlap or incompatible with each other. The method was reported to applicable in various 2-dimensional and 3-dimensional fluid-structure interaction. However, examples were only given for cases of the 2-dimensional problem. Although the method handles elastic solids and compressible fluids easily but can still handle elastic-plastic solids and incompressible fluid systems. The method is weak in dealing with highly complex structures, corners and edges. To solve the problem involving cracks might be very challenging using this method. There is a need to handle the activation of an additional degree of freedom [87].

Hu et al. presented some development and modifications of the *Arbitrary Lagrangian-Eulerian method* (ALE). The method involved the combination of fluid and particle motion governing equations. The equations of motion for the fluid and particles are discretized in a moving, unstructured finite element mesh via spatial discretization scheme. Also, equations governing the motion of a fluid are discretized in a finite difference mesh via the temporal discretization scheme. Fluid and particle positions are updated explicitly, while their motions are updated implicitly. The method was used to simulate migration and sedimentation of spheres in both Newtonian and viscoelastic fluids. Behaviors of particles such as drafting-kissing-tumbling are observed. The evolution and time-line of suspensions are studied and demonstrated [88].

Peskin introduced the mathematical structure of *the immersed boundary method* (IB), for numerical simulation of fluid-solid, fluid-fluid interactions. It involves a mixture of Lagrangian and Eulerian parameters. The Eulerian parameters were defined at fixed mesh points in a cartesian coordinate, while the Lagrangian parameters were defined in a curvilinear mesh that passes through the fixed cartesian grid without adapting to any constraint condition. The Eulerian and Lagrangian variables are related by an interaction equation consisting of Dirac delta function which is approximated to provide a smooth transition between the cartesian and curvilinear grid. The IB method was initially intended to study flow around the heart valves but has gotten accepted in various applications. The method was also intended to bridge the sharp transition between fluid dynamics and elasticity, therefore, it is applied to many visco-elastic incompressible flow systems. The versatility of the immersed boundary applied mostly but not limited to biofluid dynamic modelling [89]. Husain and Floryan developed the *spectrally-accurate algorithm* based on

Immerse boundary (IB) conditions. The algorithms are developed to compute problems with moving boundary. A flow domain was immersed in a computational domain with internal constraints as the boundary conditions. Discretization in a direction normal to the wall uses Chebyshev expansion while Fourier expansion was used for discretization in the flow direction. Fourth-order implicit temporal discretization was implemented. The performance of the algorithm was reported to be in good agreement with the theoretical prediction. Several numerical solvers were tested and evaluated for the algorithms. To obtain faster computational results and low memory consumption, a new class of solver was proposed. This solver will take advantage of the coefficient matrix structure [79].

Liu et al. developed the *sharp interface cartesian grid method* and combined with *Ghost fluid method (GFM)* to simulate droplet dynamics on impact and spreading on a surface of arbitrary shape. Finite difference method was used to discretize the Navier stokes equations on a cartesian grid. The GFM is essential for liquid-liquid interfaces, while the Sharp interface method was used for Solid-liquid interfaces. They combine sharp interface ghost fluid method has successfully accounted for the effect of discontinuities such as density and viscosity jumps as well as singular sources such as surface tension both in droplet and bubble simulations. Large deformation of the moving boundary was successfully captured through Level-set representation [90]. Pak and Chang, in order to estimate pressure drop and collection efficiency in a venturi scrubber, a model was developed. In a venturi scrubber liquid droplets, dust and gas interaction exist therefore the developed model provides a solution to three-phase flow involving liquid, solid and gas. The gaseous phase is treated as a continuum and solved using the Navier-stokes equation in a Eulerian approach while the discrete solid and liquid phases are solved by using the Basset-

Boussinesq-Oseen (B-B-O) equation in the Lagrangian approach. Atomization, deformation, break up of liquid droplet and collision and capture of the liquid droplet with dust was simulated using the Eulerian-Lagrangian approach. The results obtained in the numerical model for pressure drop and collection are in good agreement with the experimental data [91].

Porcheron applied the *mean-field approximation on the lattice gas model* and determined the effect of nanostructure pillar height on density distribution and contact angle of the water droplet on a solid rough surface. It is reported that for the case of smooth surface, contact angles are well described by the young's equation. Considering a rough surface with an array of nanostructured pillars. Two different behaviors were observed as the pillar height increases. First, the liquid penetrates the pillars and contact angle increases continuously as the pillar height increases. This behavior is similar to Wenzel equation, although the value of the contact angle is underestimated. Second, the liquid did not penetrate the inter pillar volume to a large extent, hence the droplet contact angle did not change with an increase in the pillar's height. This behavior is much similar to Cassie-Baxter equation for contact angle on heterogeneous surfaces [92]. Jeong et al. studied the behavior of water droplet on a pillar-type nanostructure under static and dynamic conditions using the *molecular dynamic simulation*. The effect of pillar height, lateral and gap dimensions were investigated. It was reported that different shapes of water droplet were observed while changing the surface parameters. Depending on three conditions; static state of the droplet, nature of the pillar-type surface, and the magnitude of the applied body force, the dynamic behavior of the droplet can be classified into three groups [93].

Lucas and Tomiyama reported the effect of lateral lift force on poly-dispersed bubbly flow. The critical bubble diameter at which the lift force changes sign obtained from an extensive experimental database. Dispersed bubbly flow, slug flow, churn –turbulent flow with high void fraction were considered in this study. In all case, turbulence flow happens in the liquid phase. The study focused on air-water and steam-water flow systems. Bubbly diameter, not less than 1 mm was investigated. Smaller size bubbles are discussed in the previous work [94].

2.7 Establishing a research gap for spinning water droplet dynamics

In this work, we reviewed the theoretical, experimental and numerical studies on dust fouling effect on the PV performance, the coating characteristics for hydrophilic and hydrophobic surfaces, surface-droplet interfacial energy and its effect on droplet dynamics, the mechanism of droplet impacting, rolling and sliding as well as the contact line dynamics of liquid droplets on horizontal and inclined hydrophobic surfaces. Also, the numerical algorithms that are developed to simulate the multiphase flow problems such as liquid droplets motion in the air and air bubbles motion in liquid, and general fluid-structure interaction, are studied.

There are various methods of dust cleaning from PV and other solar energy harvesting devices such as natural, mechanical, electrical and coating method. The natural method is not practicable in commercial-scale Solar plant. The mechanical methods require lots of material and energy and mechanical methods such as brushing can cause damage to the

surface and it's difficult for large PV systems and in frequent dusty environment. The electrical method is not efficient for larger dust particles, and for effective dust cleaning the electrical method cannot be used as a standalone method. The coating method provides a natural way of self-cleaning, therefore require low cost, low energy consumption, eco-friendly and low maintenance requirement. Considering the importance of coating method for dust cleaning and other applications such as heating and cooling, various theoretical and empirical models were developed to predict the liquid droplet impacting, rolling and sliding on coated surfaces. To exploit the application of liquid droplets in dust cleaning, more dynamic motions of the droplets need to be studied such as spinning as it has not been fully studied in the existing literature.

Dust mitigation by droplet rolling creates striation-like textures around the droplet path due to droplet wobbling. Therefore, the spinning of rolling droplets is expected to minimize this effect. A droplet rolling down an inclined flat hydrophobic surface has a contact angle hysteresis that depends on the surface energy and also contributes to rolling and sliding motion. So also, droplet moving on an inclined wedge channel formed by two different hydrophobic surfaces will experience a relative difference in surface energy between the two surfaces. This difference is predicted to add a spinning motion in the droplet dynamic. Hence, the contact line dynamics of water droplet undergoing these three motions becomes essential.

CHAPTER 3

METHODOLOGY

In this chapter, we adopted three different approaches to solve the problem. These approaches are applied in a logical sequence given as follows; (1) Analytical, (2) experimental, and (3) numerical methods. The purpose of adopting three different methods in the study is to have a reliable and optimum solutions for droplet dynamics in wedge structures. Analysis of droplet motion based on force balance within the droplet and at the contact surface between the droplet and hydrophobic surface formed the basis of the Analytical modelling. The effect of all parameters of interest in this study is first access via the analytical approach in order to effectively design the experimental study. The experimental study is designed to validate the analytical model and also to study other parameters of interest not captured by the analytical model. Lastly, we adopted the numerical study in order to study the internal fluidity, contact line dynamics, pressure and velocity within the moving droplet using Conservative level set algorithms.

3.1 Analytical methodology

3.1.1 Surface adhesion energy

The effort to minimize the surface energy via several approaches results in the formation of hydrophobic and superhydrophobic surfaces. Adhesion energy of liquid droplets on surfaces depends on the degree of surface hydrophobicity. Since adhesion energy affects the rolling and sliding of water droplet down an inclined superhydrophobic surface,

therefore a water droplet moving in a wedged channel formed by two surfaces of different hydrophobic will result in rolling, sliding and spinning motion. The total translational velocity can be determined through vector addition of these three velocities, but the contribution of each component depends on the nature of the surface among other factors.

Liquid droplet on an inclined plane experiences a number of forces. A liquid droplet remains stationary on a plane surface provided the total forces acting on the droplet are in equilibrium, that is when the resultant force is zero. When the plane is slightly tilted, body force continuously increases until the body force becomes in equilibrium with friction, drag and adhesion forces. The angle at which is droplet starts to roll and slide down an inclined plane is determined by surface energy, which is a function of contact angle. liquid droplet on inclined surfaces undergoes deformation as shown in Figure 3.1 contact angle hysteresis of the deformed droplet determines the nature of droplet motion. That is, when the contact angle hysteresis becomes large, the droplet motion is more of sliding than rotation.

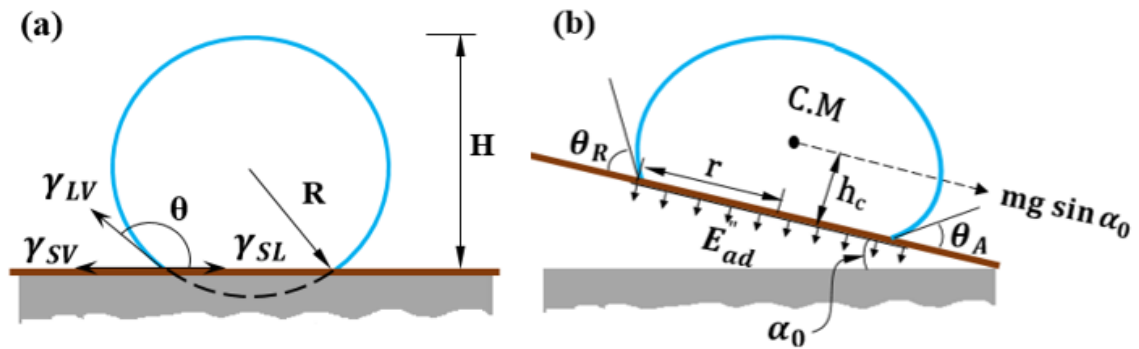


Figure 3.1: (a) Water droplet on a horizontal hydrophobic surface (b) Water droplet starts to slide and rotate down the inclined surface.

Assuming the droplet to have a spherical shape as shown in Figure 3.1(a), the relationship between the droplet radius, height, base diameter and contact angle is given in Eqs. 3.1 and 3.2 [57].

$$H = R(1 - \cos \theta) \quad (3.1)$$

$$D_{Base} = 2R \sin \theta \quad (3.2)$$

Young's equation governs the droplet shape in static or dynamic equilibrium. Therefore, the shape of the droplet depends on the following;

- ✓ The droplet fluid properties
- ✓ The nature of the contact surface
- ✓ The surrounding medium

$$\gamma_{SL} + \gamma_{LV} \cos \theta = \gamma_{SV} \quad (3.3)$$

where θ is the equilibrium contact angle. R is the radius of the droplet assuming spherical shape, γ_{LV} is the surface tension. γ_{sv} is the surface free energy and γ_{SL} is the interfacial energy. The surface adhesion energy can be determined through the following relations;

$$E_{ad}'' = \frac{mg \sin \alpha_0 \times h_c}{A_{wet}} \quad (3.4)$$

$$h_c = \frac{R(1 - \cos \theta)(3 + \cos \theta)}{4(2 + \cos \theta)} \quad (3.5)$$

where E_{ad}'' is the surface adhesion force, α_0 is the surface inclination angle at which the droplet starts to roll and slide down the inclined superhydrophobic surface, h_c is the height of the center of mass of the liquid droplet, m is the droplet mass.

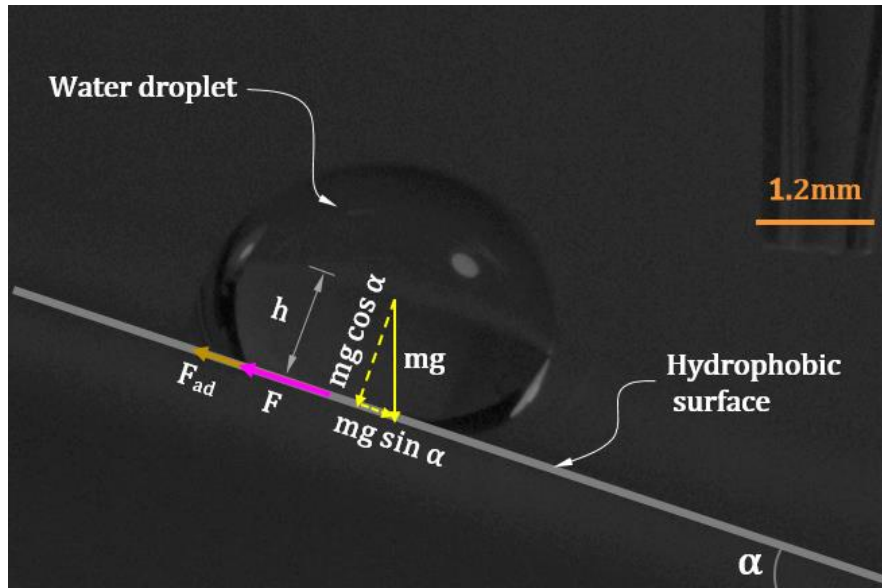


Figure 3.2: Forces that govern liquid droplet dynamics on an inclined plan

3.1.2 Dynamics of a liquid droplet on wedge channel

Liquid droplet on an inclined hydrophobic channel has interesting behavior different from that of the flat inclined plane. Analysis of droplet dynamics base on force and energy balance reveals the dynamical nature of droplet motion. In this section, we are going to

analyze the effect of droplet size, inclination angle, wedge angle and nature of surfaces in droplet motion down the inclined wedge.

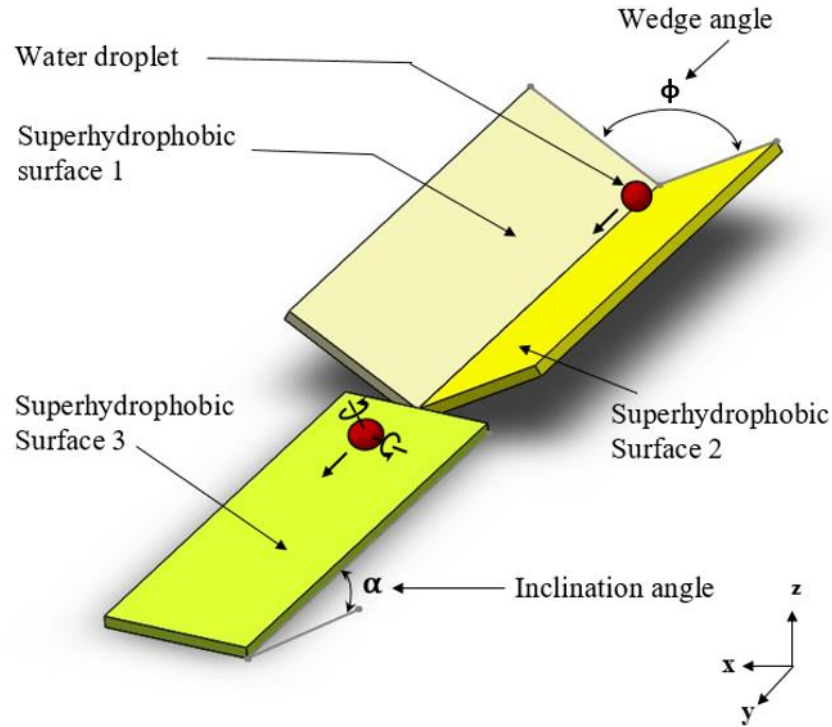


Figure 3.3: Three-dimensional view of the problem

Figure 3.3 shows how two surfaces of different hydrophobic properties formed a wedge upon which a liquid droplet rotate and spin while propagating in a straight path. The forces acting on the liquid droplet are shown in 2-dimensional views in Figure 3.4, while the liquid droplet is assumed to maintain a spherical shape. The shape of the liquid droplet approximates a sphere provided the size of the liquid droplet is very small. However, this model is not applicable provided the size of the droplet becomes large.

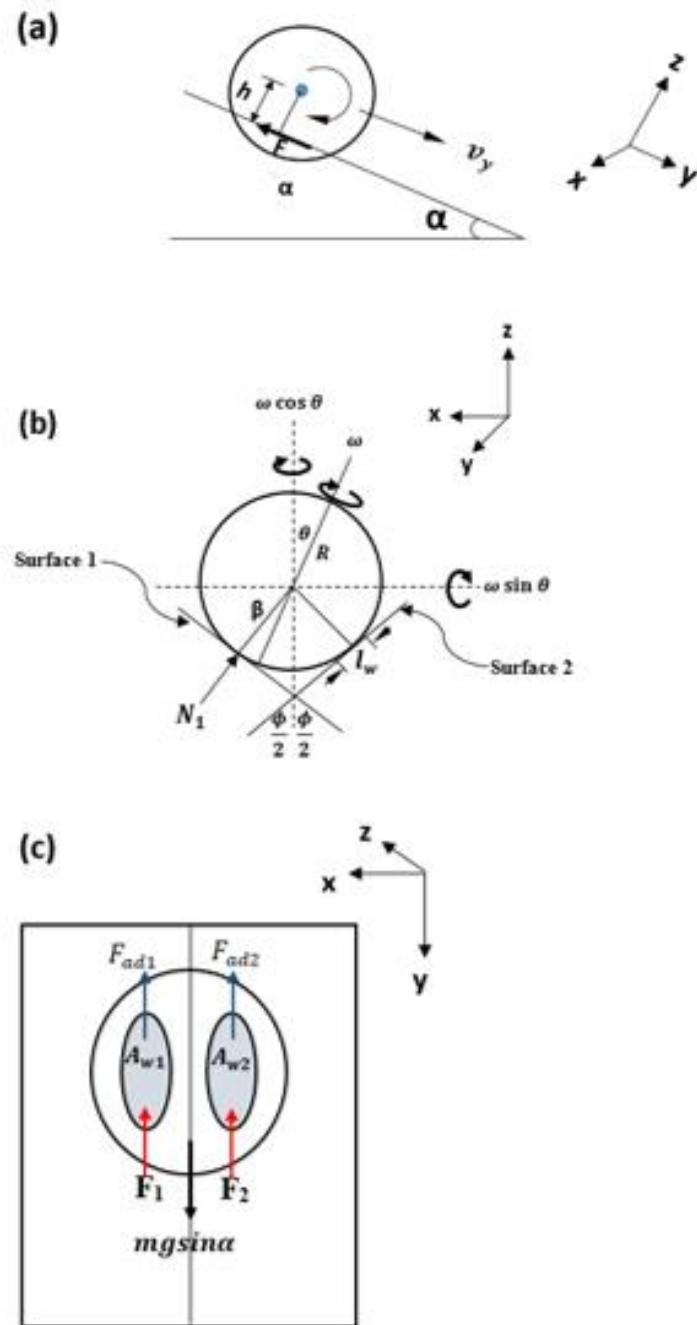


Figure 3.4: Two-dimensional view of the problem.

3.1.3 Balance of forces and moment

Considering the summation of all forces along the x-axis, the components of forces in the x-direction constitute only that of the normal reaction force as given in Eq. (3.6) and (3.7).

$$\Sigma F_x = 0 \quad (3.6)$$

$$N_1 \cos \alpha \sin \beta - N_2 \cos \alpha \sin \beta = 0 \quad (3.6)$$

For the summation of forces along the y-axis, i.e. down the inclined plane, acceleration of the droplet can be expressed as:

$$\Sigma F_y = m \frac{dv_y}{dt} \quad (3.7)$$

$$mg \sin \alpha - 2F - F_{ad1} - F_{ad2} = m \frac{dv_y}{dt} \quad (3.8)$$

where, α is inclination angle, mg is the droplet weight, F is frictional force and F_{adi} are the adhesion forces.

The frictional coefficient for the two surfaces have the same order of magnitude (i.e. $\mu_1 \sim \mu_2 \sim \mu$) as determined experimentally [95], and the same normal reaction force is acted on the two surfaces (i.e. $N_1 = N_2 = N$). Adhesion forces are determined by droplet contact angle on the surfaces.

$$F_1 = F_2 = \mu N \quad (3.10)$$

Considering the summation of forces along the z-axis,

$$\Sigma F_z = 0 \quad (3.11)$$

$$2N \cos \beta - mg \cos \alpha = 0 \quad (3.9)$$

$$N = \frac{mg \cos \alpha}{2 \cos \beta} \quad (3.13)$$

It is important to note that, the change in droplet center of mass is considered to be negligible. Therefore, the wetting area of the droplet remains relatively constant on wedge plate surfaces while the droplet assumed to be a spherical shape with wetted surfaces on wedge plates during its motion down the inclined wedge channel [96].

Considering the summation of angular momentum of the droplet along x-axis

$$\Sigma \tau_x = I \alpha_x \quad (3.14)$$

where I is the moment of inertia about x-axis and α_x is the rotational angular acceleration.

$$h(2F + F_{ad1} + F_{ad1}) = \int_0^{h+R} \frac{1}{2} m r^2 dr * \frac{1}{h} \frac{dv_y}{dt} \quad (3.15)$$

where, h is height of the center of mass. Since spherical droplet is assumed, the moment of inertia becomes:

$$\int_0^{h+R} \frac{1}{2} m r^2 dr \approx \frac{2}{5} m R^2 \quad (3.16)$$

Eq. (3.15) becomes:

$$h(2F + F_{ad1} + F_{ad1}) = \frac{2}{5}m \frac{R^2}{h} \frac{dv_y}{dt} \quad (3.17)$$

$$2F + F_{ad1} + F_{ad1} = \frac{2}{5}m \frac{R^2}{h^2} \frac{dv_y}{dt} \quad (3.18)$$

By eliminating the adhesion and friction force by substituting Eq. (3.18) into Eq. (3.9), a constant acceleration term is obtained (i.e. Eq. (3.19)).

$$\frac{dv_y}{dt} = \frac{mg \sin \alpha}{m + 2mR^2/5h^2} \quad (3.19)$$

From Fig. 3.4 (b), h can be expressed as:

$$h = R \sin \frac{\phi}{2} \quad (3.20)$$

$$\frac{dv_y}{dt} = \frac{mg \sin \alpha}{m + 2m/5 \sin^2 [\phi/2]} \quad (3.21)$$

$$\frac{dv_y}{dt} = \frac{g \sin \alpha}{1 + \frac{2}{5 \sin^2 (\phi/2)}} \quad (3.22)$$

$$v_y = \frac{gt \sin \alpha}{1 + \frac{2}{5 \sin^2 (\phi/2)}} \quad (3.23)$$

where α is the inclination angle of the plane, ϕ is the wedge angle formed by the two surfaces and v_y is the linear velocity of the droplet down the inclined wedge channel. Hence, Eq. (3.22) and (3.23) show that the translational acceleration of the droplet down the inclined wedge channel depends only on the wedge and inclination angles [97].

By considering the angular momentum of droplet along z-axis (i.e. along the droplet height), the spinning motion of the liquid droplet caused by the difference in the adhesion forces at the contact areas can be predicted.

$$\sum \tau_z = I \alpha_z \quad (3.24)$$

where I is the moment of inertia about the z-axis, and α_z is the spinning angular acceleration.

$$F_{ad1} R \sin(\beta) - F_{ad2} R \sin(\beta) = I \frac{d\omega_z}{dt} \quad (3.25)$$

From Fig. 3.4 (b), β can be expressed as

$$\beta = 90 - \frac{\phi}{2} \quad (3.26)$$

The adhesion forces create the spinning velocity of the droplet. Therefore, the rolling and spinning angular velocities as shown in Fig. 3.4 (b) are given as follow:

$$\omega_x = \omega \sin \theta \text{ and } \omega_z = \omega \cos \theta \quad (3.27)$$

Hence, Eq. 3.25 yields:

$$F_{ad1}R \cos\left(\frac{\phi}{2}\right) - F_{ad2}R \cos\left(\frac{\phi}{2}\right) = I \frac{d[\omega \cos \theta]}{dt} \quad (3.28)$$

$$F_{ad1}R \cos\left(\frac{\phi}{2}\right) - F_{ad2}R \cos\left(\frac{\phi}{2}\right) = I \left[-\omega \sin \theta \frac{d\theta}{dt} + \cos \theta \frac{d\omega}{dt} \right] \quad (3.29)$$

$$\frac{(F_{ad1} - F_{ad2})R \cos \frac{\phi}{2}}{\frac{2}{5}mR^2} = \left[-\omega \sin \theta \frac{d\theta}{dt} + \cos \theta \frac{d\omega}{dt} \right] \quad (3.30)$$

Since the parameters in the LHS of Eq. (3.30) remain constant with time, we can denote the LHS as K :

$$K = \left[-\omega \sin \theta \frac{d\theta}{dt} + \cos \theta \frac{d\omega}{dt} \right] \quad (3.31)$$

The constant K can be determined from material properties of droplet fluid and the two surfaces that make up the wedge.

The transitional velocity of the droplet down the inclined wedge channel (i.e. along the y-axis) can be obtained also from:

$$v_y = \omega_x h = h\omega \sin \theta = R\omega \sin \theta \sin \frac{\phi}{2} \quad (3.32)$$

Hence, the derivative of v_y in Eq. (3.32) can be obtained as:

$$\frac{dv_y}{dt} = R \sin \frac{\phi}{2} \left(\sin \theta \frac{d\omega}{dt} + \omega \cos \theta \frac{d\theta}{dt} \right) \quad (3.33)$$

Multiply Eq. (3.32) by Eq. (3.33)

$$\frac{v_y dv_y}{dt} = R^2 \omega \sin^2 \frac{\phi}{2} \left(\sin^2 \theta \frac{d\omega}{dt} + \omega \sin \theta \cos \theta \frac{d\theta}{dt} \right) \quad (3.34)$$

Using Eq. (3.31) to eliminate $\frac{d\theta}{dt}$ in Eq. (3.34)

$$\frac{v_y dv_y}{dt} = R^2 \omega \sin^2 \frac{\phi}{2} \sin^2 \theta \frac{d\omega}{dt} + R^2 \omega \sin^2 \frac{\phi}{2} \cos \theta \left[\cos \theta \frac{d\omega}{dt} - K \right] \quad (3.35)$$

$$\frac{v_y dv_y}{dt} = R^2 \omega \sin^2 \frac{\phi}{2} \left[(\sin^2 \theta + \cos^2 \theta) \frac{d\omega}{dt} - K \cos \theta \right] \quad (3.36)$$

$$\frac{v_y dv_y}{dt} = R^2 \omega \sin^2 \frac{\phi}{2} \left[\frac{d\omega}{dt} - K \cos \theta \right] \quad (3.37)$$

Eq. (3.37) is the ordinary differential equation (ODE) governing the motion of the droplet down the inclined wedge channel. For the present study, the variable of interest is the resultant angular velocity (ω). Hence, v_y and can be eliminated from the ODE using Eq. (3.22) and Eq. (3.23):

$$\frac{dv_y}{dt} = \frac{g \sin \alpha}{1 + \frac{2}{5 \sin^2 (\phi/2)}} \quad \rightarrow \quad v_y = \frac{g t \sin \alpha}{1 + \frac{2}{5 \sin^2 (\phi/2)}}$$

$$\sin \theta = \frac{v_y}{R\omega \sin \frac{\phi}{2}} = \frac{g t \sin \alpha}{R\omega \sin \frac{\phi}{2} \left(1 + \frac{2}{5 \sin^2 (\phi/2)} \right)} \quad (3.38)$$

$$\cos \theta = \sqrt{1 - \frac{\left(1 + \frac{2}{5 \sin^2 (\phi/2)} \right)^2}{R^2 \omega^2 \sin^2 (\phi/2)}} \quad (3.39)$$

Substitute Eq. (3.22), (3.32) and (3.39) into Eq. (3.37) leads to:

$$\frac{d\omega}{dt} = \frac{a^2 t}{R^2 \omega \sin^2 (\phi/2)^2} + K \sqrt{1 - \frac{a^2 t^2}{R^2 \omega^2 \sin^2 (\phi/2)}} \quad (3.40)$$

where, a is the linear acceleration derived in Eq. (3.22) as $\frac{dv_y}{dt}$

By denoting $A = \frac{a^2}{R^2 \sin^2 (\phi/2)} \sim s^{-4}$, the governing ODE is obtained for $\omega =$

$f(K, R, \alpha, \phi, t)$ as:

$$\frac{d\omega}{dt} = \frac{At}{\omega} + K \sqrt{1 - \frac{At^2}{\omega^2}} \quad (3.41)$$

This shows that the resultant angular acceleration of the rolling and spinning droplet is a nonlinear ODE of first order and depends on inclination angle, wedge angle, nature of the two hydrophobic surfaces, properties of droplet fluid, and size of droplet.

The solution to the non-linear ODE is determined from wolfram alpha (Mathematica Program) to be:

$$\omega(t) = \sqrt{t^2(A + K^2) + 2Kte^{c_1} + e^{2c_1}} \quad (3.42)$$

Imposing the initial condition, $\omega(0) = 0$, a specific solution is obtained as:

$$\omega = t\sqrt{(A + K^2)} \quad (3.43)$$

Upon seeking solution for ω , the inclination of spinning axis (θ) can be obtained from Eq. (3.38) as:

$$\theta = \sin^{-1} \left(\frac{g t \sin \alpha}{R t \sqrt{(A + K^2)} \sin \frac{\phi}{2} \left(1 + \frac{2}{5 \sin^2(\phi/2)} \right)} \right) \quad (3.43)$$

Hence, rolling (or rotation) angular velocity, $\omega_x(t, A, K, \alpha, \phi, R)$ can be obtained as:

$$\omega_x = \omega \sin(\theta) = \frac{g t^2 \sin \alpha}{R \sin \frac{\phi}{2} \left(1 + \frac{2}{5 \sin^2(\phi/2)} \right)} \quad (3.44)$$

Therefore, it can be seen that the rolling speed, ω_x , is only dependent on time, inclination angle, wedge angle and droplet size.

Also, the spinning angular velocity, $\omega_z(A, K, \phi, R)$ can be expressed as:

$$\omega_z = \sqrt{\left(t^2(A + K^2) - \frac{\left(1 + \frac{2}{5 \sin^2(\phi/2)} \right)^2}{R^2 \sin^2(\phi/2)} \right)} \quad (3.45)$$

Hence, unlike the rolling speed, it can be seen that the spinning speed (ω_z) is a function of the fluid property, droplet size, hydrophobic surface wetting state and wedge angle.

3.1.4 Material properties required in the analytical model

The constant K which represent the materials property term can be determined as follows:

From mass and volume relation;

$$m = \frac{4\rho\pi R^3}{3} \quad (3.46)$$

$$K = \frac{F_{ad1}R \cos(\frac{\phi}{2}) - F_{ad2}R \cos(\frac{\phi}{2})}{\frac{8\rho\pi R^5}{15}} \quad (3.47)$$

The adhesion forces; F_{ad1} and F_{ad2} were determined to be [95];

$$F_{ad1} = \frac{48}{\pi^3} \gamma_{LV} R f_1(\cos \theta_{R1} - \cos \theta_{A1}) \quad (3.48)$$

$$F_{ad2} = \frac{48}{\pi^3} \gamma_{LV} R f_2(\cos \theta_{R2} - \cos \theta_{A2}) \quad (3.49)$$

$$K = \frac{90 \gamma_{LV} [f_1(\cos \theta_{R1} - \cos \theta_{A1}) - f_2(\cos \theta_{R2} - \cos \theta_{A2})]}{\rho \pi^4 R^3 \cos(\frac{\phi}{2})} \quad (3.50)$$

$$K = \frac{120 \gamma_{LV} [f_1(\cos \theta_{R1} - \cos \theta_{A1}) - f_2(\cos \theta_{R2} - \cos \theta_{A2})]}{\rho \pi^3 V \cos(\frac{\phi}{2})} \quad (3.51)$$

$$K \sim s^{-2}$$

where; γ_{LV} is the surface tension of droplet material. θ_{R1} , θ_{A1} , θ_{R2} , and θ_{A2} are the advancing and receding contact angles of surface 1 and surface 2, respectively. f is the solid surface fraction, R is the radius of the droplet before deformation, V is the droplet volume, ω is the angular speed of the droplet down the plane, ρ is the density of droplet material, ϕ is wedge angle formed by the two surfaces.

Table 3.1: Properties of distilled and Superhydrophobic surfaces.

S/N	Property	Name	Value	Unit
1	ρ	Density	997.1	Kg/m ³
2	γ_{LV}	Surfaces tension	7.2×10^2	N/m
3	f_1	Solid fraction	0.6	1
4	θ_{A1}	Advancing angle, surface 1	158	Degree
5	θ_{R1}	Receding angle, surface 1	132	Degree
6	f_2	Solid fraction	0.4	1
7	θ_{A2}	Advancing angle, surface 2	161	Degree
8	θ_{R2}	Receding angle, surface 2	159	Degree

3.1.5 Total kinetic energy

During the motion of the droplet a combination of rotation, spinning, and sliding motions creates a 3-dimensional velocity that determines the overall kinetic energy of the moving droplet. The total kinetic energy is determined by summing up the three components (rotation, spinning and sliding kinetic energy). The kinetic energy components are added via scalar addition as shown in Eq. (3.52), However, the total velocity vector is determined through velocity vector addition as shown in Eq. (3.54).

$$(E_{total})_{k.e} = (E_{rotation})_{k.e} + (E_{spinning})_{k.e} + (E_{sliding})_{k.e} \quad (3.52)$$

$$\frac{1}{2}mv_{tot}^2 = \frac{1}{2}mv_{rot}^2 + \frac{1}{2}mv_{spin}^2 + \frac{1}{2}mv_{slid}^2 \quad (3.53)$$

$$v_{tot}^2 = v_{rot}^2 + v_{spin}^2 + v_{slid}^2 \quad (3.54)$$

$$v_{tot} = \sqrt{v_{rot}^2 + v_{spin}^2 + v_{slid}^2} \quad (3.55)$$

Rotational, spinning and sliding velocities are normalized with the total velocity, while experimental is normalized with capillary time to control the effect of droplet size on wobbling frequency.

$$t_c = \sqrt{\frac{m}{\gamma_{LV}}} \quad (3.56)$$

$$t^* = t/t_c \quad (3.57)$$

$$v_{rot}^* = v_{rot}/v_{tot} \quad v_{spin}^* = v_{spin}/v_{tot} \quad v_{slid}^* = v_{slid}/v_{tot} \quad (3.58)$$

where t_c is the capillary time, m is the mass of the droplet, γ_{LV} the surface tension of water, t^* is the normalized time, v_{rot}^* , v_{spin}^* and v_{slid}^* is the normalize rotational, spinning and sliding velocities.

3.1.6 Validation of Analytical model with experimental data

The analytical model for rotational angular velocity is validated with experimental data for different cases of droplet size, plane inclination angle and wedge angle, as shown in Figures 3.5.

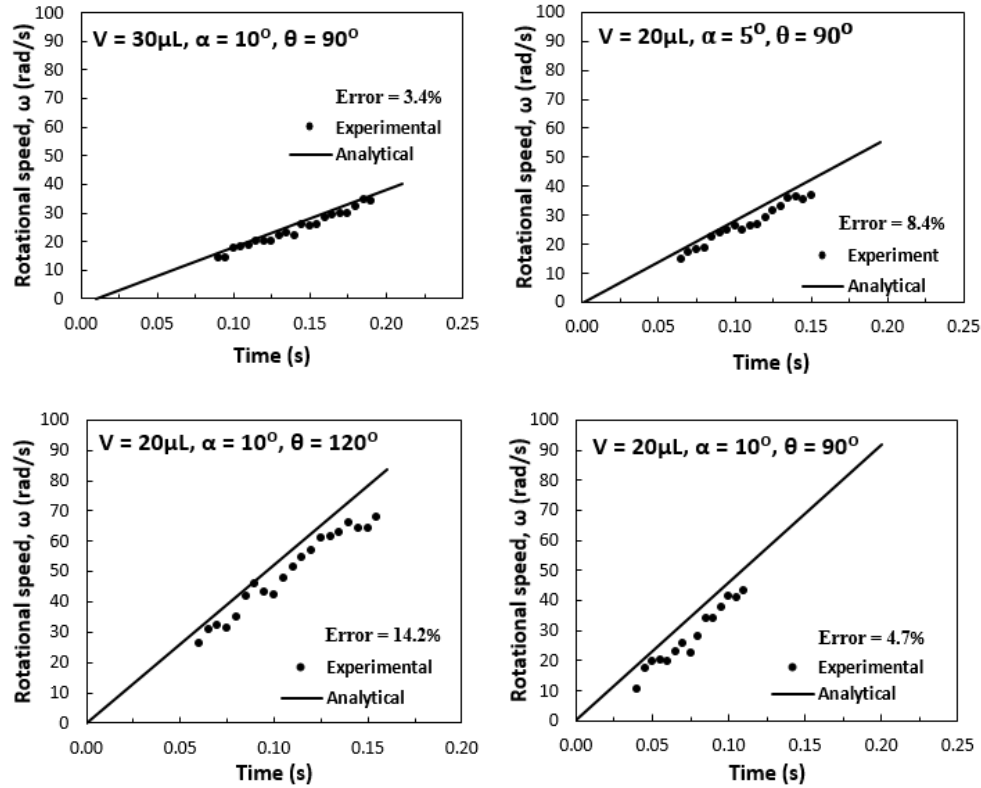


Figure 3.5: Comparison of experimental data with the theoretical model

Four cases of experimental data are compared with the derived analytical model and results shows that the model is valid with an average of less than 10% error. The analytical model is mainly derived to investigate the effect of parameters on spinning and rolling of liquid droplet. The parameters under study which include; (1) droplet size, (2) inclination angle, (3) wedge angle.

3.2 Experimental methodology

Polycarbonate surfaces were crystallized with acetone for four minutes to generate the nano-size fibrils like structure. To improve the wetting state of the surface from hydrophobic (contact angle $\sim 120^\circ$) to superhydrophobic (contact angle $\sim 150^\circ$) silicon nano-particles were deposited through dip coating. Two different surfaces with different wetting states were generated and tested. Using an Optical tensiometer the contact angles for the two surfaces are in the order of 140° and 150° . The two surfaces are placed side by side to form the v-shaped wedge channel and a water droplet is placed at the line of contact between the surfaces. The wedge channel is inclined while the motion of the water droplet is recorded using a high-speed camera. Rolling, sliding and spinning motions of water droplets are observed and the effect of droplet size, inclination and wedge angles on rolling, sliding and spinning are studied.

3.2.1 Experimental equipment and materials

Equipment

The equipment used during the development of hydrophobic surface, testing surface properties, creation of an experimental platform, recording experimental data, and processing result include;

1. Cutting machine (Vertine universal band sawing machine)
2. Grinding machine (Metallographic sample grinding-polishing machine, MOPAO260)

3. Transmittance test (Jenway Model 6705 Scanning UV/Visible spectrophotometer)
4. High-speed camera (DANTEC DYNAMICS SpeedSense)
5. Transferpette
6. Stand
7. Electric lamp
8. Computer
9. VCA optima contact measurement
10. Glue gun
11. 3D printer



Cutting machine



Grinding machine



Transmittance testing machine



High speed camera



Transferpetter



Stand



Computer system



Lamp



3D printer



Contact angle measurement



Glue gun

Figure 3.6: Equipment used in the experimental stages.

MATERIALS

The materials used in the experiment are the consumables which include;

1. Polycarbonate (PC)
2. Glass
3. Acetone
4. 3D printed wedge platform.
5. Distilled water
6. Carbon-nanotube (CNT)
7. Scotch tape
8. Superglue

3.2.2 Experimental procedures

The experimental stages involved in this work are separated into three: (1) In the first stage, the coated glasses and polycarbonate wafers are developed. (2) The wedge platform is developed as a 3-dimensional draw and printed in a 3D printer. (3) In the third stage, the motion of water droplet is studied.

a) Preparation of surfaces

In the first stage of the experiment, two glass samples were cleaned and placed in a silica based solution via dip-coating technique. The nature and pattern of the coated glass samples were test under scanning electron microscope (SEM) as shown in Figure 3.7 (a) and (b). Also, a polycarbonate (PC) sheet was cut into wafers of $3\text{cm} \times 7\text{cm}$ dimensions. The wafers were polished in a grinding machine to enhance a better quality and appearance. The surfaces of two PC samples were placed in a pool of acetone for four (4) minutes to create a solution crystallized surface. The crystallized surfaces were cleaned in a pool of distilled water and placed in the airstream for one minute to enhance the required surface microstructures. The acetone crystallization created nanostructure hairy patterns typical of a surface with non-wetting property. The nature and pattern of the nanoscale size hairs were investigated under a scanning electron microscope image shown in Figure 3.7 (c) and (d).

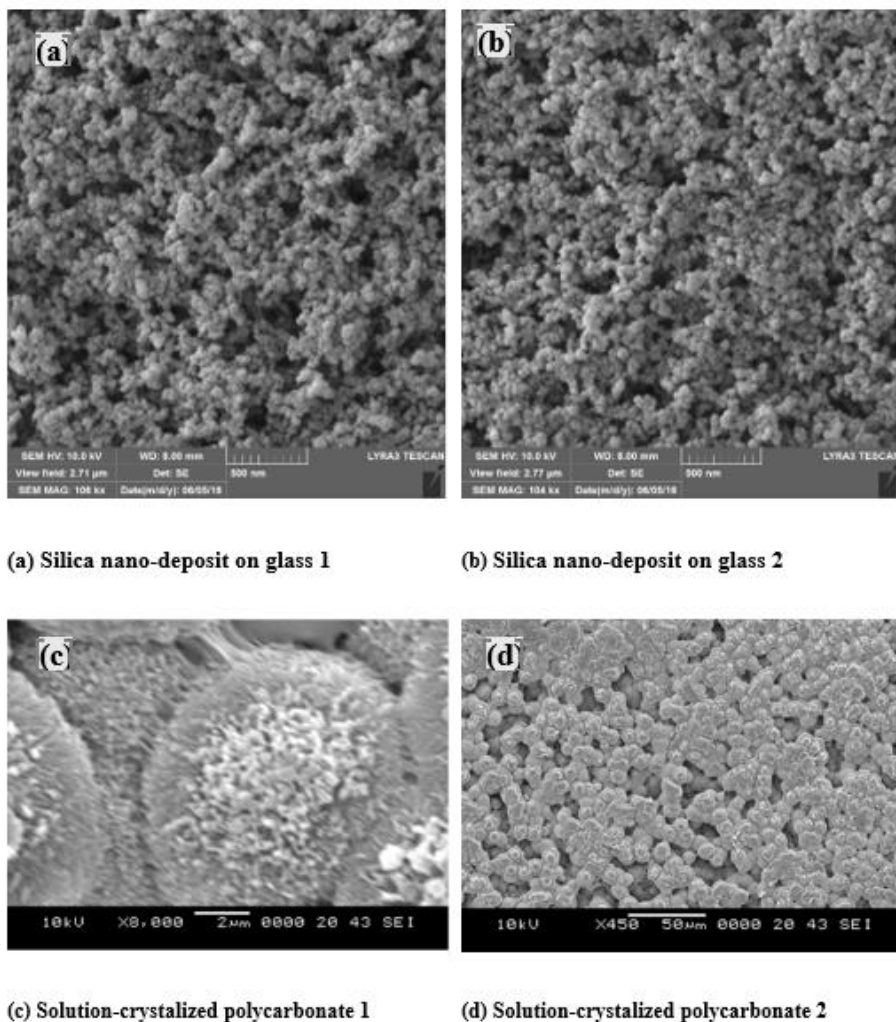


Figure 3.7: Scanning electron microscope (SEM) micrograph of the superhydrophobic surfaces developed through two different methods

Transmittance test was conducted via Jenway Model 6705 Scanning UV/Visible spectrophotometer. At the initial stage of the testing process, the UV transmittance machine was first set to baseline calibration. A sample is placed in the machine at each time and the sample transmittance is displayed via a screen and saved. The light transmitting property of pure glasses and pure PCs as well as the coated glasses and coated PCs were measured and shown Figure 3.8 and Figure 3.9.

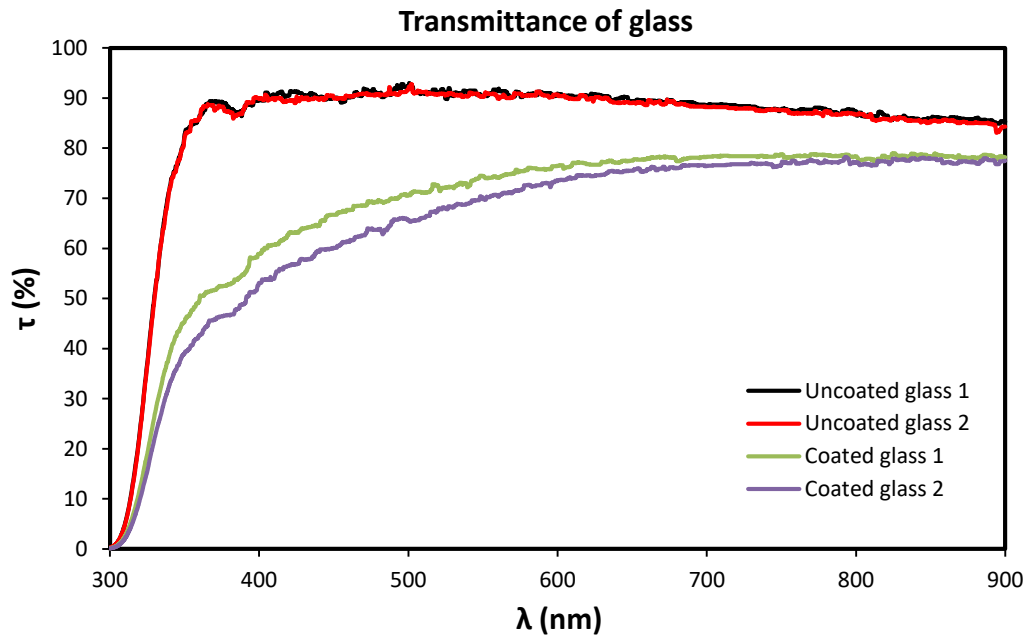


Figure 3.8: Transmittance of two uncoated and coated glass samples.

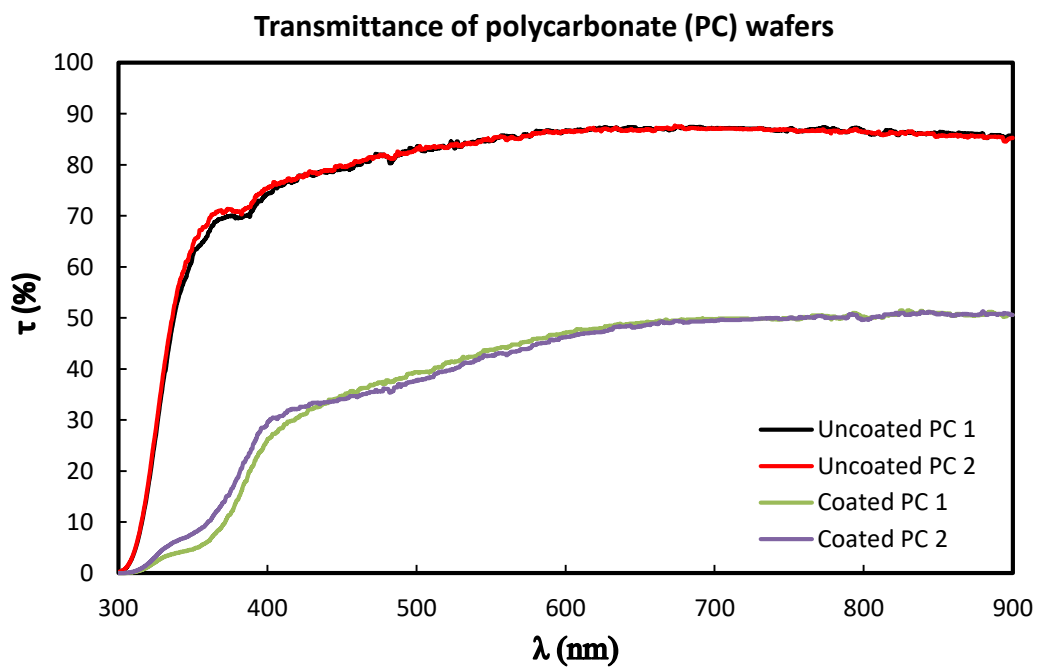


Figure 3.9: Transmittance of two uncoated and coated Polycarbonate samples.

The coated glass samples were cured in a 400K temperature medium for one hour. The surface energy of the PC and glass samples was accessed through static contact angle measurement of sessile droplets in the VCA optima contact angle measurement machine. Figure 3.10 shows the contact angle for 6 μ L sessile droplet on PC and glass samples.

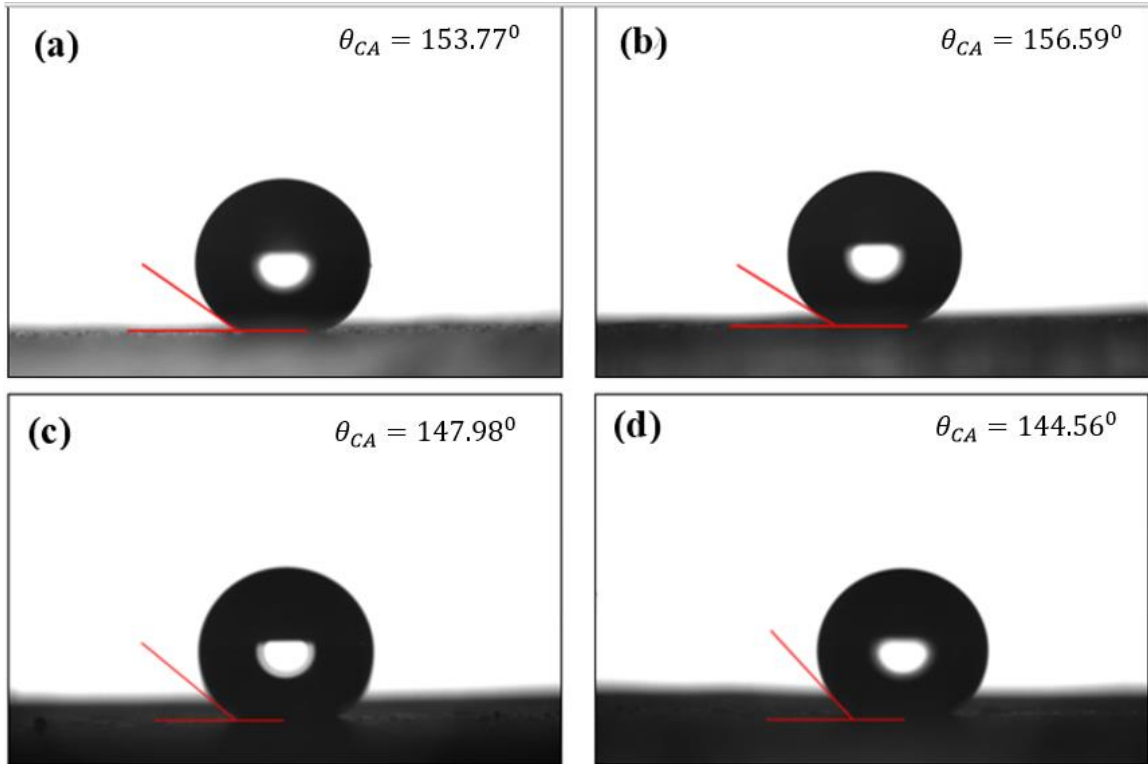


Figure 3.10: (a) and (b) Contact angle measured for two coated glass samples and, (c) and (d) contact angle measured for two coated glass samples.\

b) Preparation of 3D printed platform

In the second stage of the experimental work, we developed a 3-dimensional drawing of all the supporting components of the wedge platform as part geometries in SOLIDWORKS 2018. We saved the file as STL and exported the STL file to a 3D printer. The 3-

dimensional sketch as shown in Figure 3.2.6 constituted of different part geometries assembled. the printer part was assembled into a flexible fixture that allows for the variation of parameters under study.

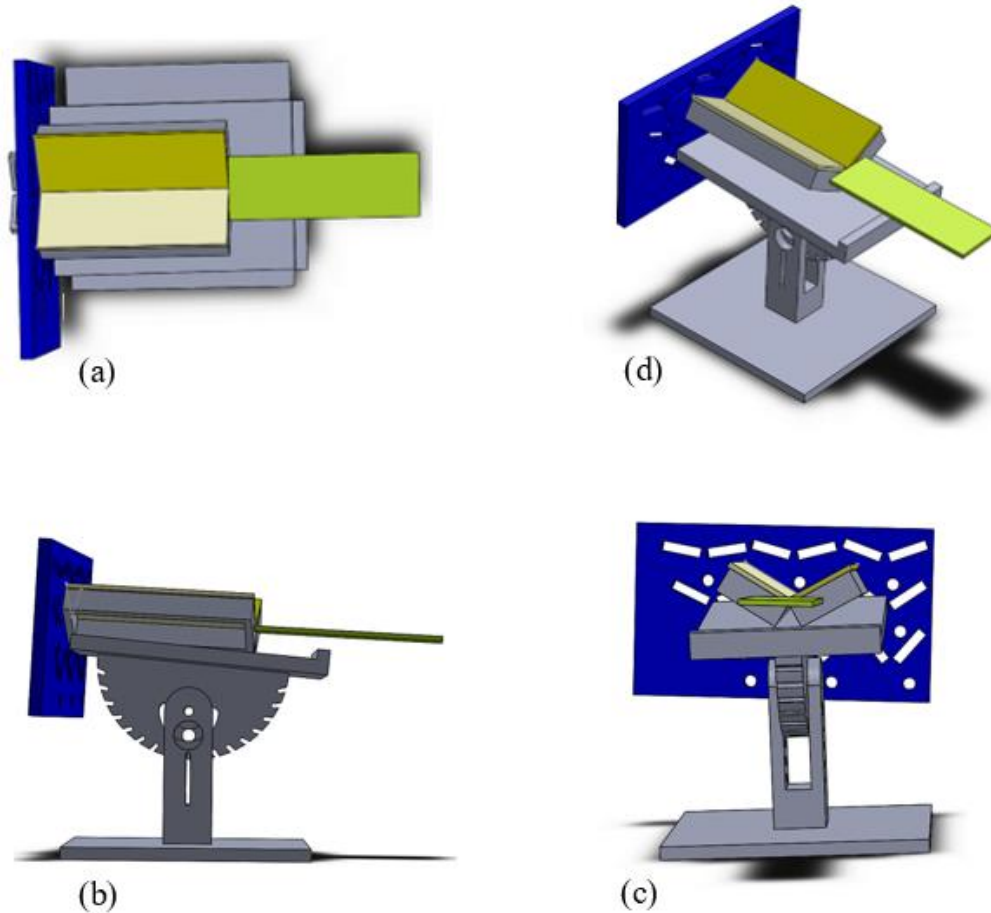


Figure 3.11: 3D printed parts, assembled and presented in different views (a) Top view (b)Side view (c) Front view and (d) Isometric view

c) Preparation of 3D printed platform

In this section, we will discuss the third stage of the experiment. The main objectives of the work were covered in this section. The experimental set-ups were shown in Figure 3.12.

which consist of an inclined wedged channel formed from two surfaces of different hydrophobicity, upon which a liquid droplet is set of rolls, spin and slide down. The motion of the liquid droplet was recorded by a high-speed camera placed at the side view to capture rotation and sliding, while a mobile camera placed at the top captured spinning motion.

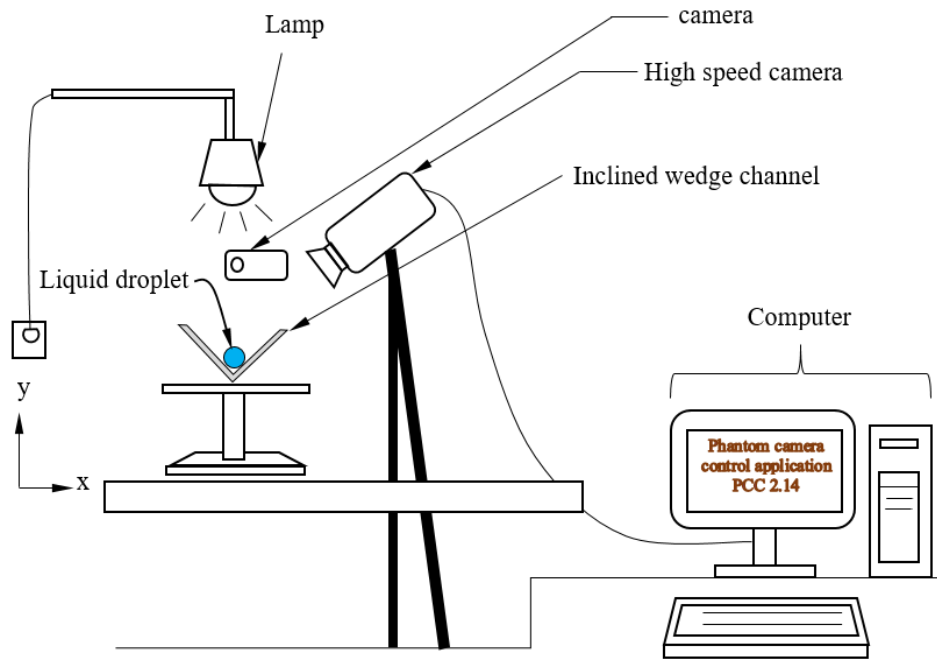


Figure 3.12: Experimental set-up for a droplet on inclined superhydrophobic wedge channel

A computer system was used to control trigger and capture of the high-speed camera via Phantom (PCC 2.14) video player. The recorded video in this software can be played at a different number of frames per second, depending on choice.

3.3 Numerical Methodology

The dynamics of the droplet on the inclined wedge of super-hydrophobic surfaces is studied numerically, using the level set model developed for two-phase laminar flow. The commercialized software COMSOL Multi-physics 5.3a was employed for the study. 3-dimensional geometry was created to represent the real experimental study domain. Materials are imported from the build-in “material library” and are assigned to each boundary. Super-hydrophobicity of surfaces is defined based on wetted wall contact angles. Laminar flow and Level set methods are the added physics and are simulated through two-way coupling in a time-dependent study. The tetrahedral mesh was adopted with mesh density controlled at the interfaces. To generate spinning droplet motion; which is the aim of the study, two models were developed. First, involves a model with two surfaces joining size-by-side to form a wedge channel (both have a contact angle of 150°), while the second case involves models with two surfaces of different contact angles, (145° and 150°), and (145 and 160). The multiphysics coupling utilized the value of surface tension of water ($\sigma = 0.072N/m$) to define the curvature of the air-water interface and then compute the velocity and pressure distribution in the droplet. The level set re-initialization parameter is set based on the maximum fluid velocity obtained from the experiment, while the parameter that controls the interfacial thickness is set as the default (i.e. twice the minimum grid element size). The level set function ϕ controls the sharp gradients of density and viscosity. Therefore, sudden changes in fluid properties which leads to singularity issue are resolved.

The initial conditions for laminar flow, level set include: i) Initial velocities = 0, ii) initial fluid 1 condition (air), $\varphi = 0$, initial fluid 2 condition (water), $\varphi = 1$, separated by level set initial interface, $\varphi = 0.5$.

Boundary conditions for laminar flow, level set include i) Wall, slip wall with slip length of average mesh thickness is assigned to bounded walls and top wall; ii) wetted wall, contact angles of $145 - 160^\circ$ is assigned to the wetted walls (contact walls); iii) Outlet, atmospheric pressure is assigned at the outlet.

The tetrahedral mesh is generated to discretize the equations of motion in all boundaries. Mesh contribution factor is used to densify the mesh in the vicinity of interfaces with a refinement factor that controls the mesh distribution.

Flow chart

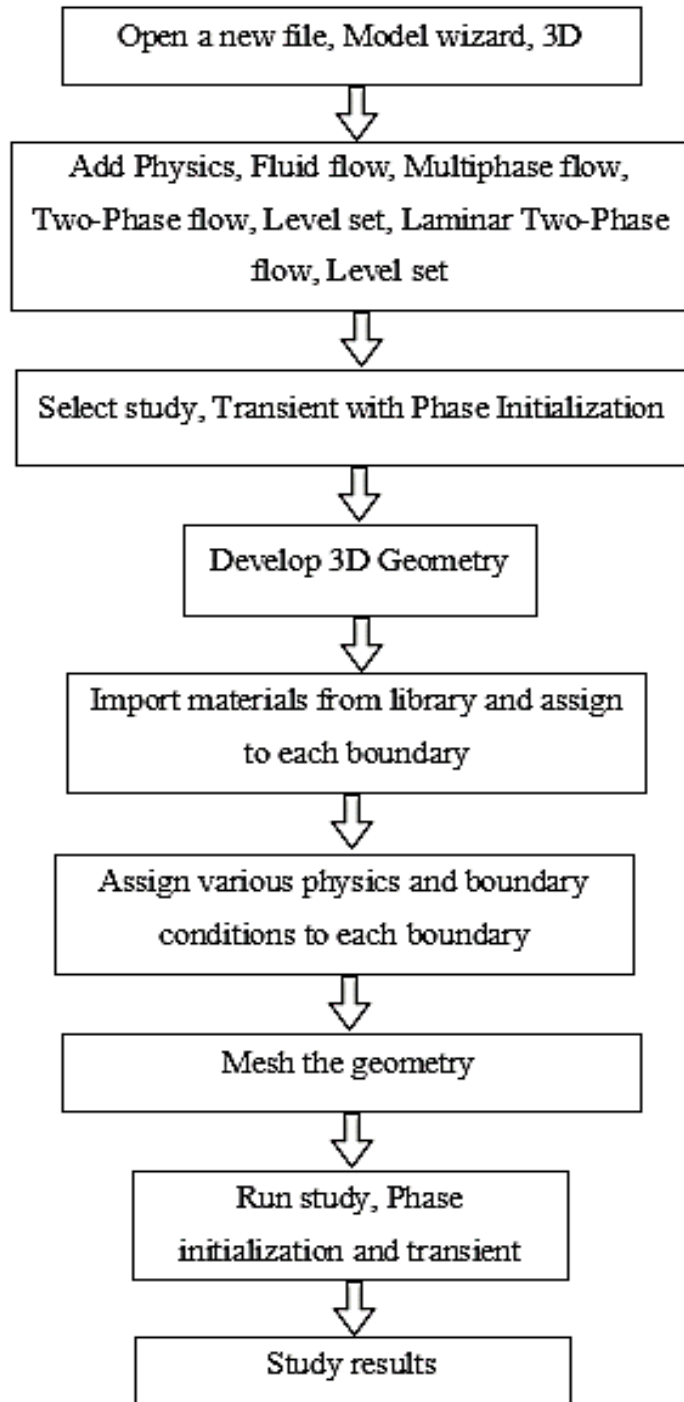


Figure 3.13: Flow chart of the numerical methodology

Geometry

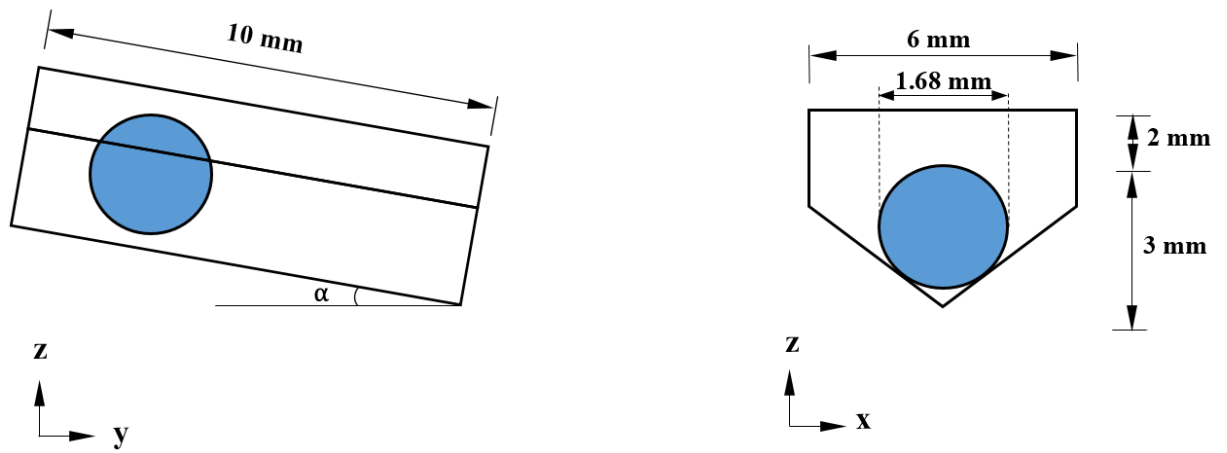


Figure 3.14: Geometry developed to study the dynamics of a liquid droplet on a wedge channel

Boundary

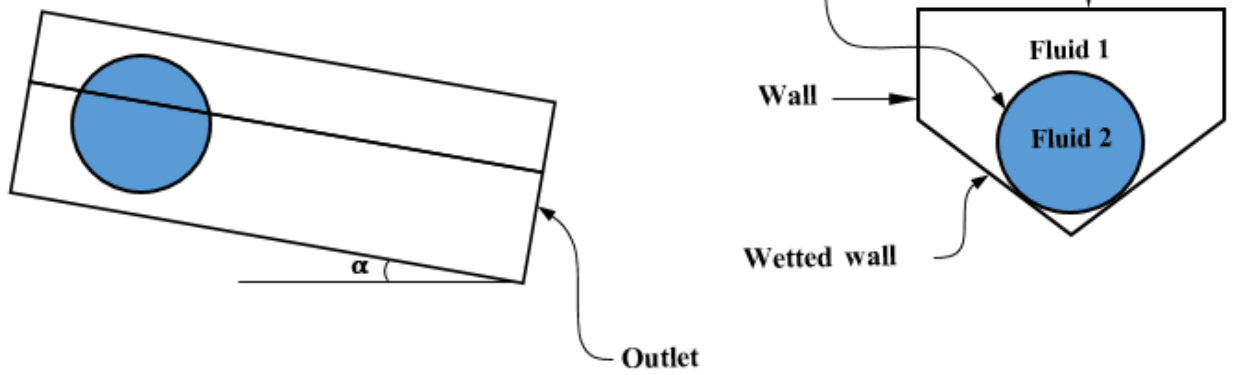


Figure 3.15: Boundaries and domains of the model geometry

Table 3.2: Domain fluids properties

property	Name	Value	unit
ρ_1	Density of fluid 1 (air)	1.225	Kg/m ³
ρ_2	Density of fluid 2 (water)	997	Kg/m ³
μ_1	Dynamic viscosity of air	1.86×10^{-5}	Pa.s
μ_2	Dynamic viscosity of water	8.9×10^{-4}	Pa.s
σ	Surface tension of water	0.072	N/m
γ	Re-initialization parameter	0.5	m/s
ϵ_{ls}	Interfacial thickness controller	0.019	mm
θ_w	Contact angle	140 - 150	°
φ	Level set interface	0.5	1

3.3.1 Governing equations

The problem involves two physics i.e. Laminar flow and level set model coupled together via a two-way coupling. The governing equations for laminar flow are the incompressible Navier-stokes equation for both the time-dependent and phase-initialization solution. The conservative Level set method is adopted. The phase initialization and transient equations governing the flow system are given as follows;

i. Laminar flow model

Time-dependent, incompressible Navier-stoke equation

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot [-\rho I + \mu(\nabla u + (\nabla u))^T] + F + \rho g \quad (3.10)$$

Phase initialization, incompressible Navier-stoke equation

$$\rho(u \cdot \nabla)u = \nabla \cdot [-\rho I + \mu(\nabla u + (\nabla u))^T] + F + \rho g \quad (3.11)$$

Continuity equation

$$\rho(u \cdot \nabla)u = 0 \quad (3.12)$$

Boundary conditions

Slip wall condition

$$u \cdot n = 0 \quad (3.13)$$

$$k - (k \cdot n)n = 0, \quad k = [\mu(\nabla u + (\nabla u))^T] n \quad (3.14)$$

Outlet condition

$$[-\rho I + \mu(\nabla u + (\nabla u)^T)]n = -(\hat{p}_0 + p_{\text{Hydro}})n \quad (3.15)$$

$$\hat{p}_0 \leq p_0 \quad p_{\text{Hydro}} = \rho_{\text{ref}} g(r - r_{\text{ref}}) \quad (3.16)$$

where r_{ref} is the reference position given by coordinate origin.

Initial values

$$u = 0 \quad (3.17)$$

$$p_{\text{init}} = p + p_{\text{hydro}}, \quad p_{\text{Hydro}} = \rho_{\text{ref}} g(r - r_{\text{ref}}) \quad (3.18)$$

ii. Conservative Level set model

$$\rho \frac{\partial \varphi}{\partial t} + \nabla(u\varphi) = \gamma \nabla \cdot \left[\epsilon_{ls} \nabla \varphi + \varphi(1 - \varphi) \frac{\nabla \varphi}{|\nabla \varphi|} \right], \quad \varphi = \text{phils} \quad (3.19)$$

where γ is the re-initialization parameter, ϵ_{ls} is the parameter controlling interfacial thickness.

φ is the level set interface defined function. Eq. (79) defines the moving interface at each position and time.

iii. Multi-physics coupling

The coupled interfaces are the flow (laminar) and the moving interface (level set).

$$F_{st} = \nabla \cdot [\sigma(1 - (n_{int} n_{int}^T))\delta] \quad (3.20)$$

where F_{st} is the surface tension force

$$\rho = \rho_1 + (\rho_2 - \rho_1)\varphi \quad (3.21)$$

$$\mu = \mu_1 + (\mu_2 - \mu_1)\varphi \quad (3.22)$$

Wetted wall condition

$$n \cdot u = 0 \quad (3.23)$$

$$-\nabla \cdot N_\varphi = 0 \quad (3.24)$$

$$F_{wall} = \sigma(n - n_{int} \cos \theta_w)\delta - \frac{\mu}{\beta}u \quad (3.25)$$

where; F_{wall} is the wall force, n_{int} is the interface normal, θ_w is the contact angle of the wetted wall, $\beta = h$ is the slip length, u is the velocity at the boundary.

iv. Particle Tracing Module

To extract information for internal fluidity within the droplet and to model the effectiveness of droplet in dust cleaning, another physics called particle tracing module is employed.

Particle release and Propagation based on Newtonian formulation, given as;

$$\frac{d(m_p v)}{dt} = F_t \quad (3.26)$$

where m_p is the particles' mass, F_t is the total force acting on particles, v is the domain fluid velocity.

Particle-wall interaction; Freeze.

$$v = v_c \quad (3.27)$$

Where v_c is the particle velocity when striking the wall.

Release;

$$q = q_0 \quad (3.28)$$

$$v = v_0 \quad (3.29)$$

Density-based release at position q_0 with initial velocity (v_0) same as domain fluid velocity field.

Drag force;

$$F_D = \frac{1}{\tau_p} m_p (u - v) \quad (3.30)$$

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \quad (3.31)$$

where F_D is the drag force from Stoke drag law, τ_p is the particle velocity response time, ρ_p is the particle density, d_p is particle diameter, and μ is the fluid dynamic viscosity

Lift force;

$$F_L = -81.2r_p^2 L_v \sqrt{\frac{\mu\rho|u-v|}{|L_v|}} \quad (3.32)$$

$$L_v = (u - v) \times [\nabla \times (u - v)] \quad (3.33)$$

where F_L is the lift force from, r_p is the particle radius, ρ is the domain fluid density, L_v is the relative velocity gradient.

Table 3.3: Particle properties

Property	Name	Value	Unit
d_p	Particle diameter	10^{-6}	m
ρ_p	Particle density	997	kg/m ³
N	Number of particles	10	1

3.3.2 Grid dependency test

The extra-fine mesh of free tetrahedral grid structure with domain elements of 2,175,389 was adopted in the study. Four meshes with different grid element sizes are created for grid independence test. Fluid-fluid and fluid-solid interfaces are made with highly dense mesh using the mesh distribution factor.

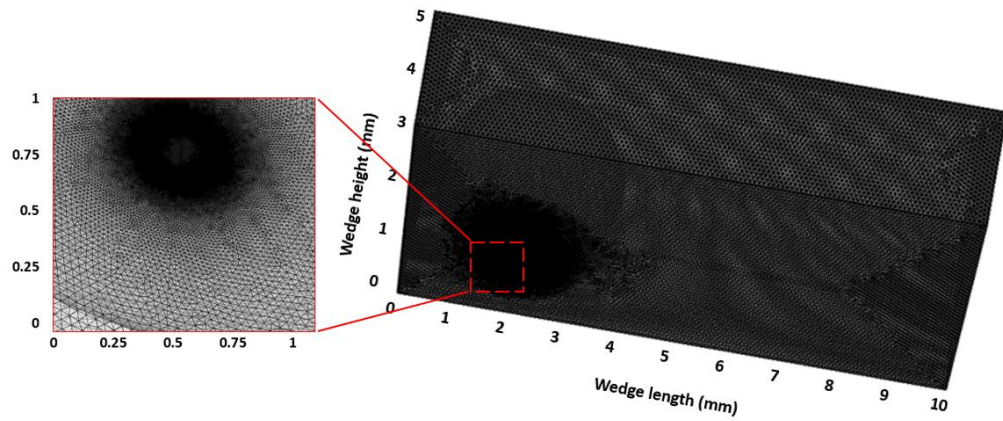


Figure 3.16: Grid used in the simulations. Finer and dense meshes were located at the water-air and water-surface interfaces

Table 3.4: Different mesh sizes developed in the study

Type	Element number	Min. element size	Max. element size
Extremely fine	9,471,536	0.00126	1.05
Extra fine	2,175,389	0.00948	0.145
Finer	568,536	0.0253	0.235
Fine	161,511	0.0632	0.335

Variation of flow parameters such as gauge pressure and velocity magnitude with mesh size was studied for all the four generated meshes at 0.04s of the flow time. An extremely dense mesh with the element size of 9,471,536 provides the best results. However, the average time taken for a single case of the solution to converge is about 20 days with a 32

processor cores workstation. As such, an extra-fine mesh with the domain element size of 2,175,389 is adopted in the study since the results obtained with the extra fine mesh are relatively close to that obtained with the extremely fine mesh. Results are also plotted for a finer mesh with the domain element size of 568,536 and fine mesh with the domain element size of 161,511. It is observed that grids with lower domain element sizes converge faster and do not demand much computational resource, however, more errors such as singularity, fluctuations and difficulty in controlling interfacial thickness. As such, the meshes are made extra finer at the water-air interface and water-surface interface as shown in Figure 3.15.

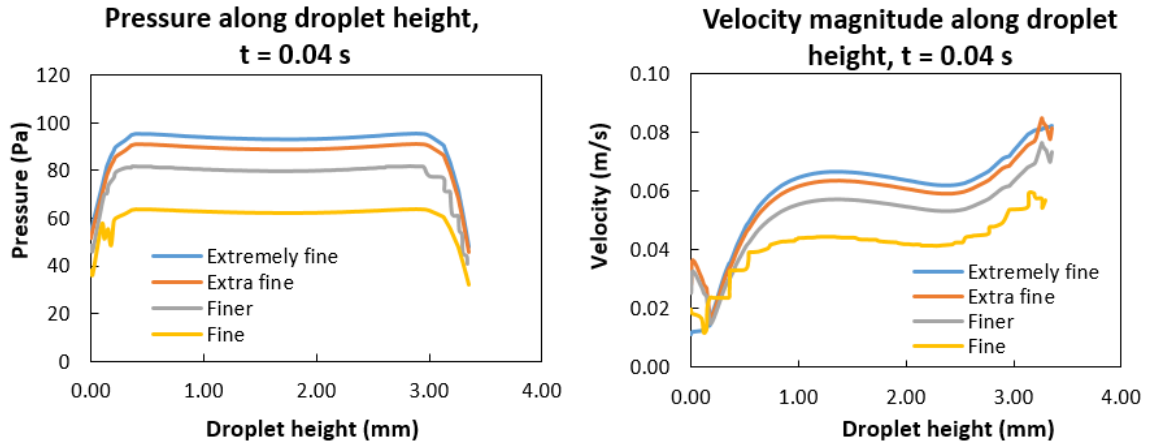


Figure 3.17: Grid independence study for velocity magnitude and Pressure variation along the droplet height from bottom to top at 0.04 s.

Interfacial thickness parameter that is set as default i.e. min. element size has a great influence on the surface tension which accounts for the lower values of both internal fluid velocities and pressure in the water droplet. The sharp jumps in the low grid number mesh as shown in Figure 3.17 is an indication of larger interfacial thickness that results from rough mesh sizes.

3.3.3 Validation of study

To validate the numerical model and analytical model, translational velocity for rolling droplet was determined experimentally and plotted along with the solution from the analytical and numerical results as shown in Figure 3.18.

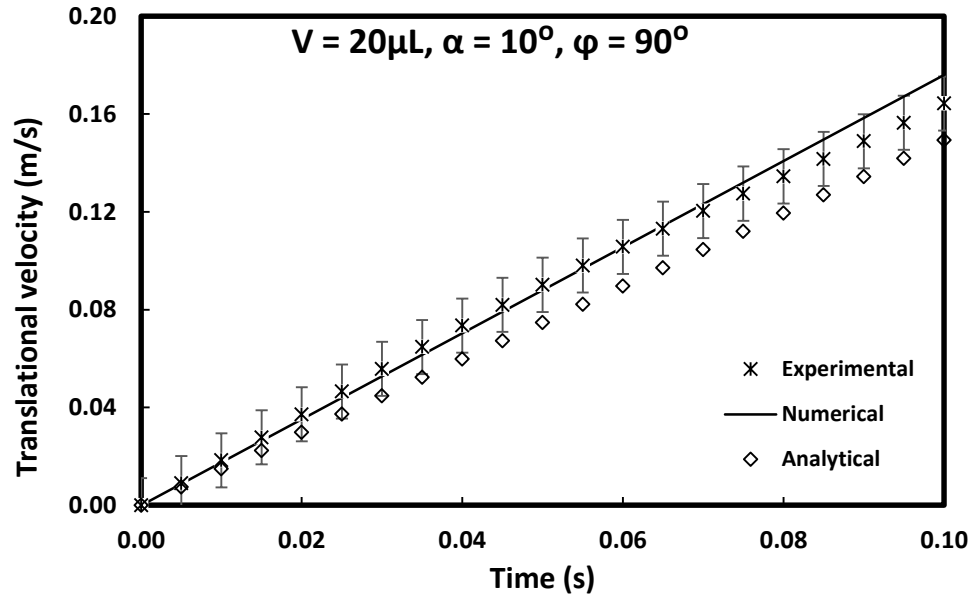


Figure 3.18: Validation of numerical model with experimental data

Considering the translational velocity of the droplet, there is a positive trend that shows how the liquid droplet is accelerating with time down the inclined hydrophobic wedged channel. At the onset of the motion, the three studies showed a very strong correlation. However, after sometimes a clear distinction is seen from the analytical model. This is an indication of the assumption of no sliding velocity made during the droplet analysis on the inclined wedge. Hence, this made the analytical plot to slightly fall before the experimental and numerical plot. A good relationship is shown in the experimental and numerical plot which indicates that the numerical model is well calibrated.

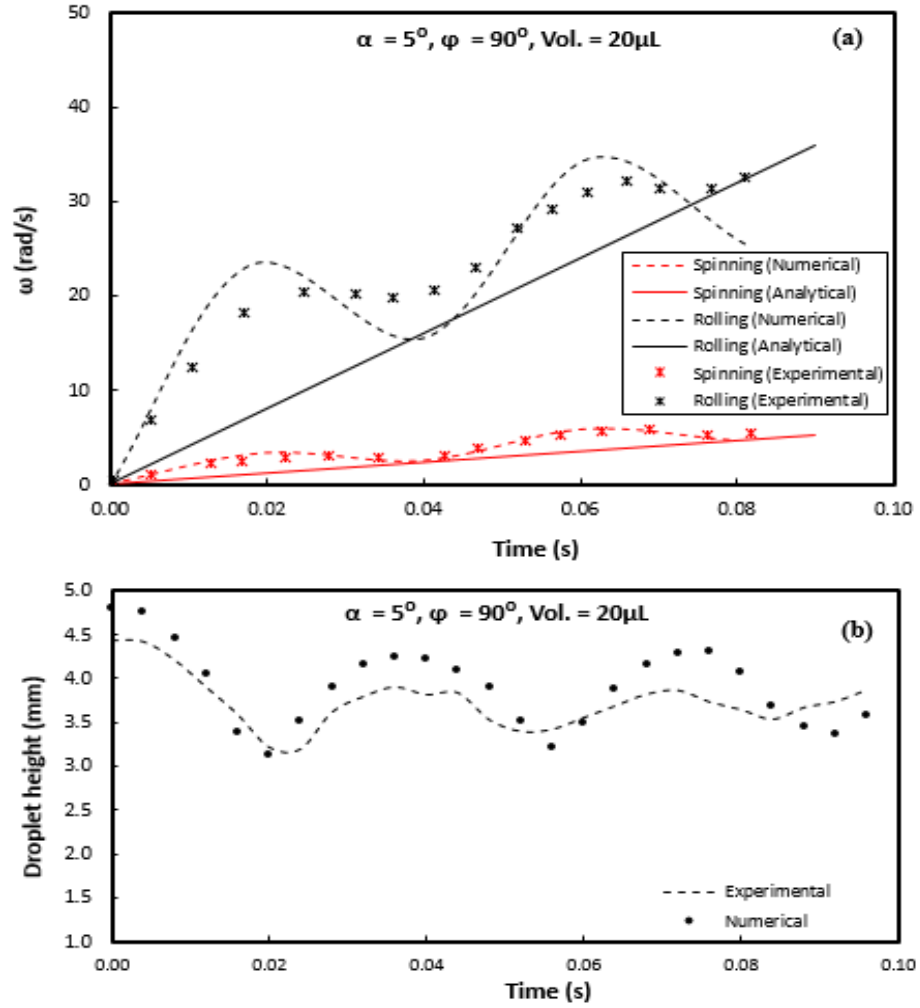


Figure 3.19: (a) Rolling and spinning velocity of a liquid droplet obtained from the analytical, experimental and numerical study. (b) The variation of droplet height during the wobbling and puddling motion on a wedged channel.

In Figure 3.19, the rolling and spinning motions, as well as the variation of droplet height, is shown. The rising and falling in the rolling and spinning angular velocity is as a result of fluctuation in the interfacial forces between the liquid droplet and the hydrophobic surface. This effect is seen in the experimental and numerical plots. Also, the droplet height changes continuously with time between the maximum and minimum droplet height

values. The degree of fluctuation of the droplet height diminishes as both the rolling and sliding velocities are rising. This shows that the effect of interfacial energy fluctuation is minimized as the droplet motion is increasing with time and position. The analytical plot has not captured the interfacial energy fluctuation. However, it shows a clear trend of the droplet motion with a good order of magnitude for rolling and spinning angular velocity.

CHAPTER 4

RESULTS AND DISCUSSION

Dust cleaning through water dynamics has been studied analytically experimentally, and numerically. Analysis of droplet motion was first conducted in order to predict the effect of the parameters in the overall solution. Furthermore, experiments were designed to validate the analytical model. Based on 90% accuracy, the analytical model was validated and applied to predict the behavior of the liquid droplet on which the main experimental study was built. Subsequently, a numerical model using the conservative level set method was developed to study the dynamics of the droplet and internal fluidity which might be difficult to study experimentally. Also, the re-initialization parameter was determined as the maximum translational linear velocity derived from the experimental result, and droplet and surface properties determined experimentally were used to calibrate and validate the numerical model.

4.1 Analytical results

To investigate the effect of parameters under study, the ordinary differential equation (ODE) generated in the analytical method was solved and presented as Eq. (3.60) ($\omega = t\sqrt{A + K^2}$). All the parameters and variables included in the analytical model are examined and their effect is plotted in a different line chart. The angular velocity of water droplet moving on a wedge channel formed by non-parallel superhydrophobic surfaces is the main output parameter under investigation. More so, the inclination of the spinning axis

places an important role in determining the spinning and rotational components of angular velocity. Therefore, other input parameters that determined the angular inclination of the spinning or rotation axis are also studied.

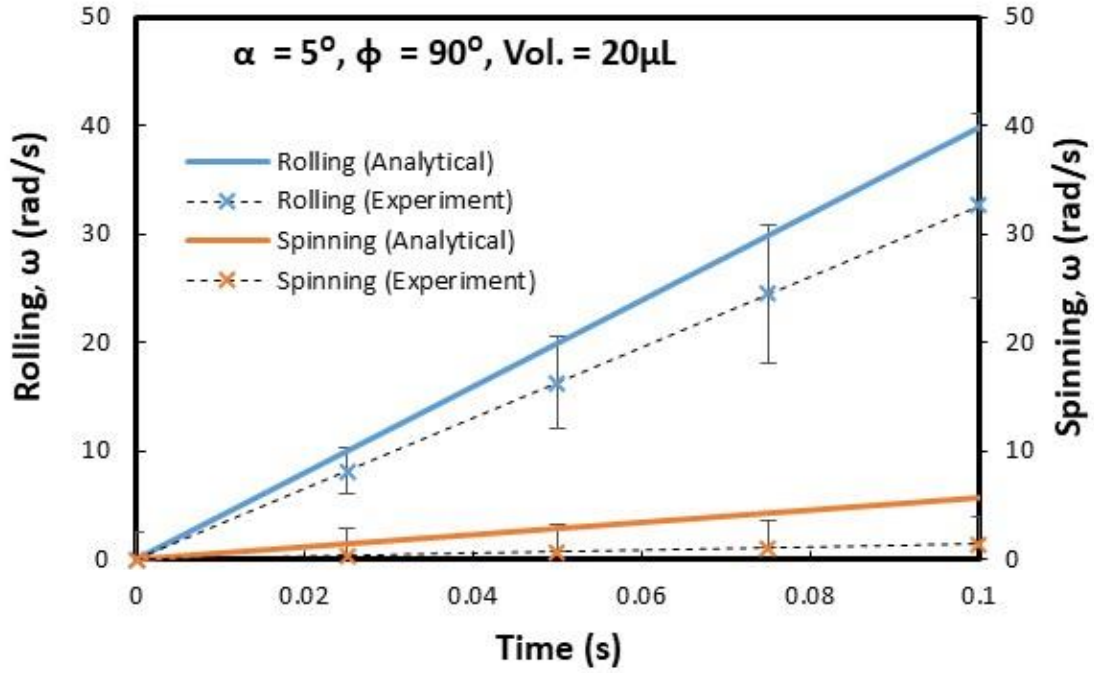


Figure 4.1: Effect of motion time on spinning and rolling angular velocity

Figure 4.1 shows the effect of flow time on both angular speed and the rotation axis of the rolling droplet on superhydrophobic wedge channel. The angular speed of the water droplet increases linearly with time on the wedge. The rolling angular acceleration is higher than the spinning angular acceleration since the top of the droplet is not restricted by any means which might retard the rolling of the droplet. whereas, the droplet spinning motion on the wedge is constricted to the difference in contact angle between the two surfaces that formed the wedged channel.

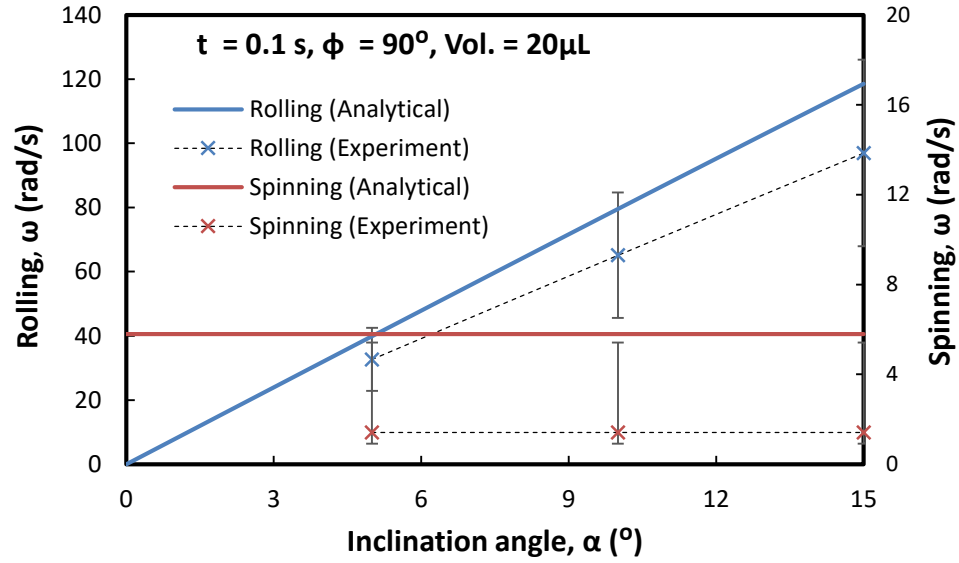


Figure 4.2: Effect of inclination angle on spinning and rolling angular velocity

Figure 4.2 shows the effect of plane inclination angle on the rolling and spinning velocity of a water droplet while other parameters such as volume, time and wedge angle are kept constant. Water droplet on a wedge of hydrophobic surfaces remains at rest when the inclination angle remains at 0° (horizontal), however, the droplet starts to roll as the wedge channel is tilt to a given angle. A linearly increasing trend pattern is observed for the plot of rolling angular velocity indicating that the rolling angular acceleration remains constant even if the plane is inclined to a higher angle. Whereas, the spinning angular velocity shows a constant value indicating that there is no acceleration of the spinning speed with the variation of plane inclination angle.

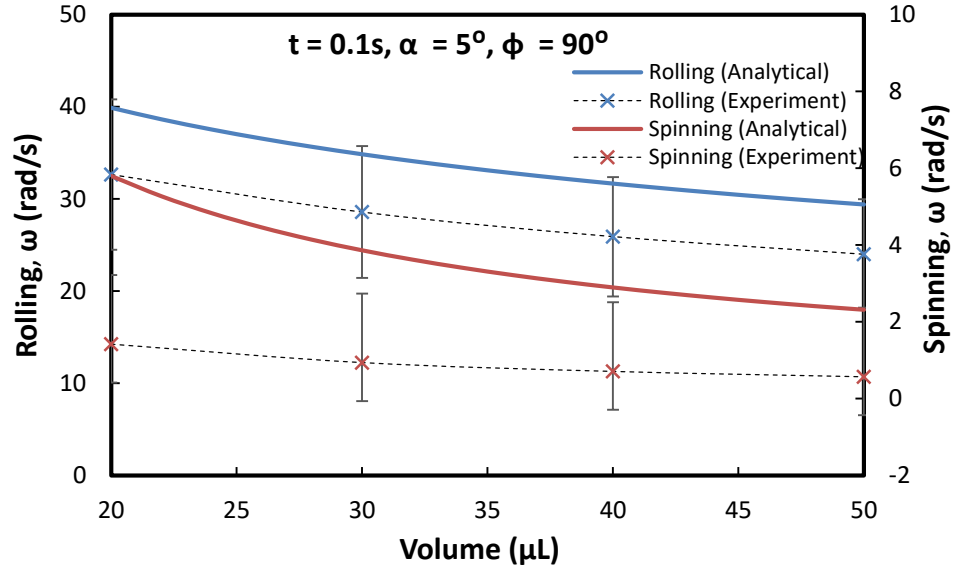


Figure 4.3: Effect of volume on spinning and rolling angular velocity

Droplet size is an important parameter that determines that roundness of water droplet on a hydrophobic surface. The validity of the analytical model largely depends on droplet size, since approximation of spherical shape was made while computing the moment of inertia of the rolling droplet. It is shown in Figure 4.3 that increase in volume leads to a decrease in both the rolling and spinning angular velocity. The fall is droplet spinning is much faster because the interfacial contact of the droplet becomes higher which in turn increases the adhesion energy thereby minimizing the free motion of the droplet.

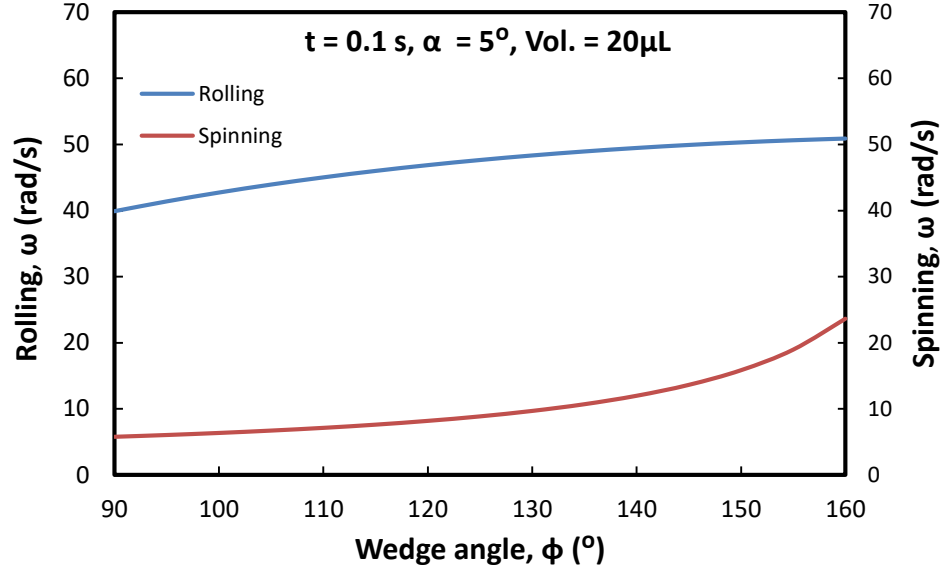


Figure 4.4: Effect of channel wedge angle on spinning and rolling angular velocity

The angle formed by the two surfaces placed side by side to make up the wedge channel was studied. Figure 4.3 shows the effect of the wedge angle on both rolling and spinning angular velocity. For the spinning angular velocity, a rise in the trend at higher wedge angle shows that the restriction to spinning motion is reduced as the wedge flattened. For the rolling angular velocity, there is a slightly positive trend as the wedge is flattened. However, the trend rises with a diminishing acceleration thereby creating a parabolic pattern.

4.2 Experimental results

The droplet motion on an inclined hydrophobic wedge channel was examined experimentally. The translational, rotational and sliding motions of the droplet are tracked with the help of suspended carbon-nanotube particles placed in a very small quantity inside the water droplet. The effects of various parameters of interest were studied, which include;

droplet size, inclination angle, wedge channel angle, nature of the two surfaces forming the wedge. The dynamic contact angles and droplet radius were measured for some specific times (0s, 0.05s and 0.1s) during the motion of the droplet. The data generated using Dantec dynamics speed sense (high-speed camera) was analyzed in a Tracker app software. Both analytical and numerical models were validated using the experimental results. Experimental data were recorded 3 times to ensure the repeatability of the recorded data. To measure the spinning and rotational velocity within the internal fluidity of the rolling droplet, the suspended carbon nanotube particles motion was tracked. The translational linear velocity is a combination of rotational, sliding and spinning velocity. The fraction of each of the three velocities depends on the flow regime, droplet size and inclination and wedge angle.

4.2.1 Normalized velocity components

To measure the velocity components (rotational, spinning and sliding), two cameras were placed at the top and side view. The translational linear velocity recorded by the Dantec dynamics speed sense (high-speed camera) placed at the side view constituted both sliding and rotational velocity. The angular speed of the carbon-nanotube particle placed inside the water droplet provides the magnitude of droplet rotational velocity. The average droplet radius during the flow regime as given in Table 4.1 (appendix) was used to compute the rotational component of translation linear velocity. Hence, the sliding velocity component is the value that remains after subtracting the rotational velocity from the total translational velocity recorded from the side view of the rolling droplet. The spinning velocity

component calculated directly from the motion of carbon nanotube particles taken from the camera placed at the top view of the water droplet.

Total velocity which determines the total kinetic energy is determined through vector addition of the three velocity components. Rotational, sliding and spinning velocities are expressed as fractional of the total velocity vector, and changes that occur in each component are given against a non-dimensional time during the droplet motion down the inclined plane. The non-dimensional time was determined from the ratio of the actual time and capillarity time.

a) Motion of droplet on inclined wedge channel

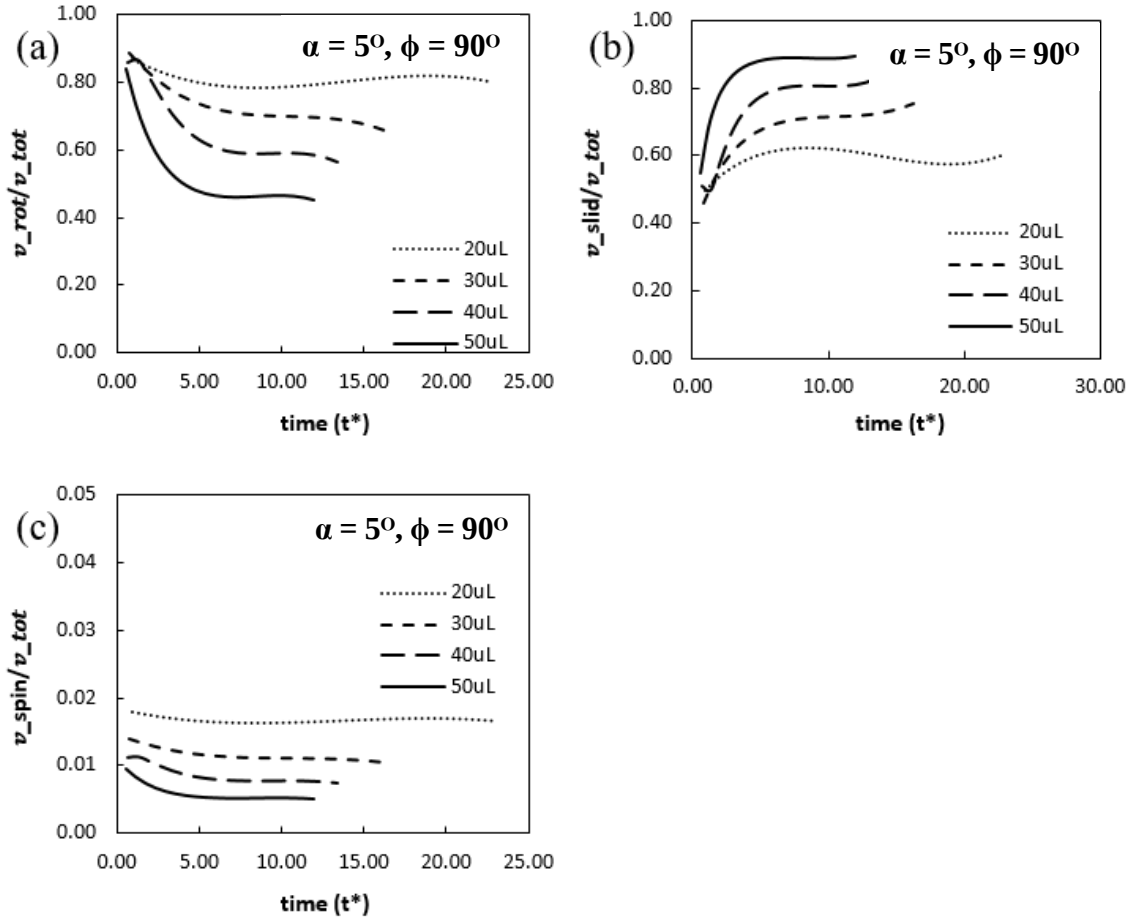


Figure 4.5: Rotational, sliding and spinning velocity express as a fractional of the total velocity vector at 5° inclined wedge channel.

In Figure 4.5 the changes in the three velocity components are given for wedge inclination angle of 5° for 20 μ L, 30 μ L, 40 μ L, and 50 μ L volume. In the initial part of the motion, there is a high contribution of rotational velocity component which falls due to a rise in the sliding velocity component. Low volume droplet shows relatively moderate changes in the three velocity components. However, higher volume droplets are more sensitive to changes due to gravitational effect on large volume droplet.

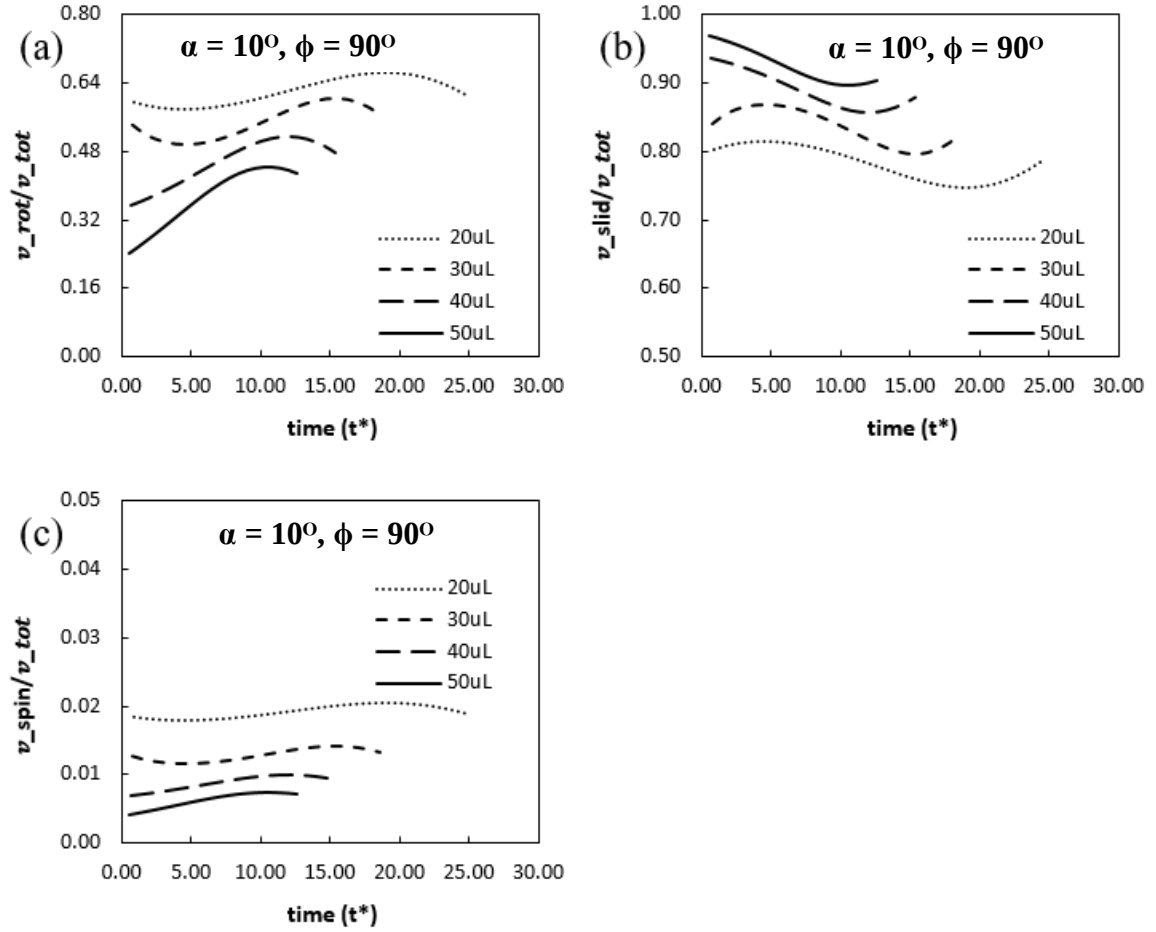


Figure 4.6: Rotational, sliding and spinning velocity express as a fractional of the total velocity vector at 10° inclined wedge channel.

In Figure 4.6 It is shown that at the initial part of the flow, the sliding component contributed more than the rotation and spinning components. The sliding velocity component increases with volume and has a negative trend during the flow regime as a result of the rise in the rotation velocity component. Low volume droplets have smaller radii. Therefore, has high rotational motion than larger volumes droplets. The spinning velocity component is higher for small volumes of the liquid droplet and a relatively slight positive trend is observed as water droplet rolls and spins down the wedged channel.

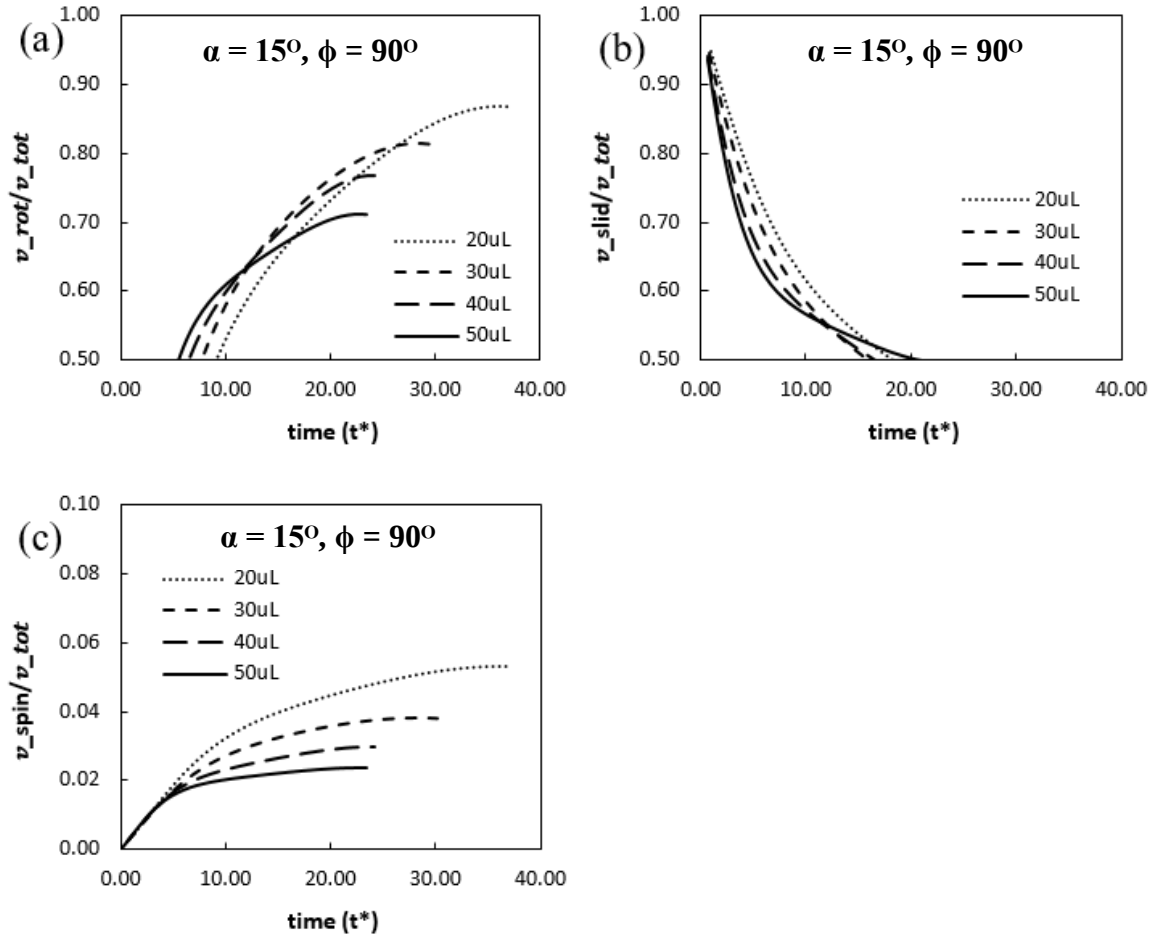
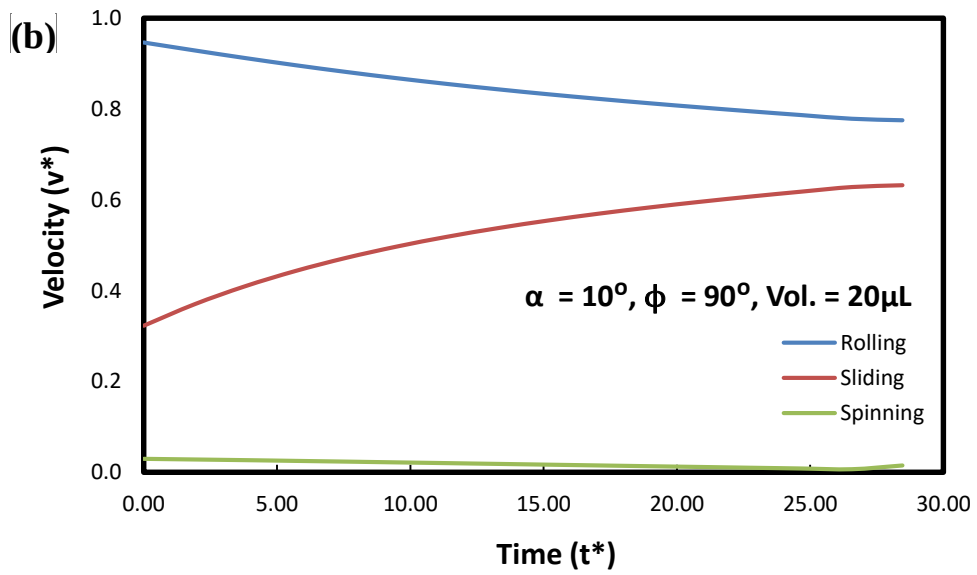
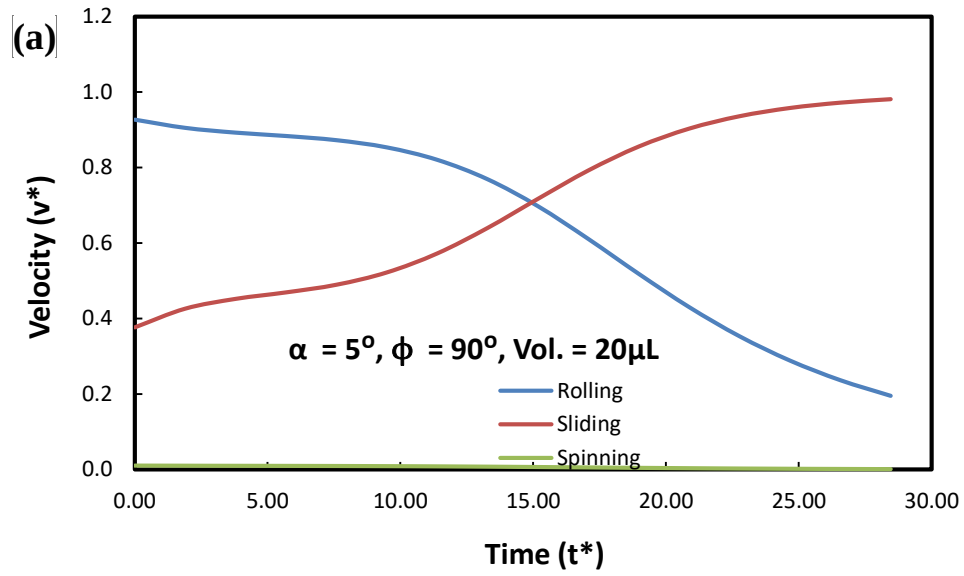


Figure 4.7: Rotational, sliding and spinning velocity express as a fractional of the total velocity vector at 15° inclined wedge channel.

In Figure 4.7 the effect of the inclination angle of the wedged channel is clearly shown. The sliding velocity component dominates the flow at the onset of droplet motion. The first contact of the droplet with the superhydrophobic surfaces creates high rotational moment within the droplet. This lead to a sudden rise in the rotational and spinning velocity components. The rotational velocity rises faster for small volume droplets and the contribution of rotational velocity dominates the flow towards the end of the flow regime.

b) Motion of droplet on flat inclined plane



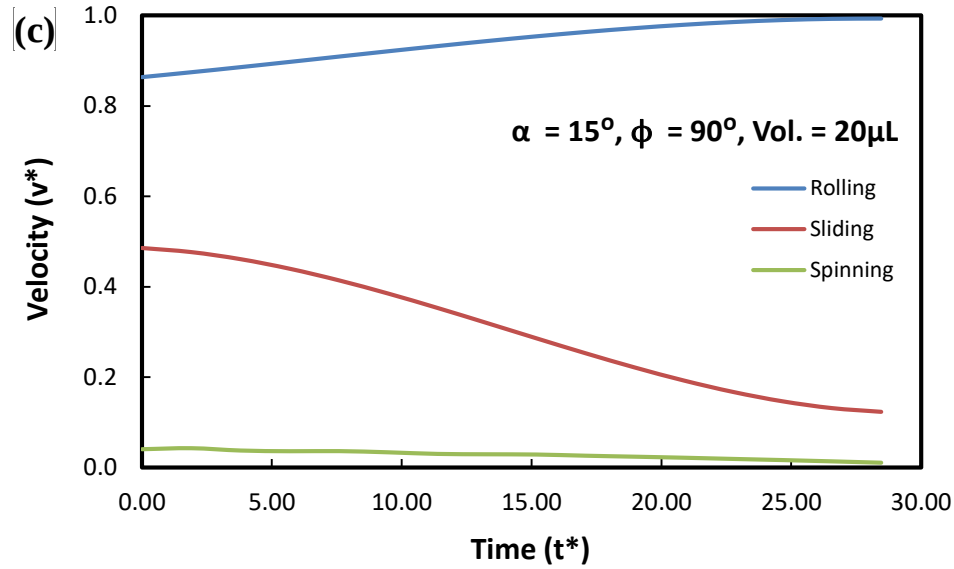


Figure 4.8: Rotational, sliding and spinning velocity express as a fractional of the total velocity vector at;
 (a) 5° inclined plane, (b) 10° inclined plane and (c) 15° inclined plane

Motion of water droplet on inclined plane starts with certain initial rolling, sliding and spinning velocities inherited from the hydrophobic wedge channel. The contribution of rolling, sliding and spinning to the total velocity vector varied with droplet motion time and with plane inclination. It is observed that at 5° inclination, the rolling velocity component starts with a very high contribution but falls rapidly due to rise in sliding velocity component. Also, when the inclination angle is increased to 10°, the fall in the rolling velocity and rise in sliding velocity component is observed to occur in a gentle gradient manner. This results from the high rotational velocity which is maintain with higher inclination, therefore, it is clearly observed at 15° inclination the rolling velocity component has an increasing trend since the high inclination angle results into continuous rise in rolling velocity much higher than sliding and spinning velocity. The spinning velocity component has the lowest contribution at all inclination, and irrespective of the

plane inclination angle, the spinning velocity shows a decreasing trend. This is due to the fact that once the liquid droplet passes the wedge channel, there is no external force that increases the spinning velocity. Therefore, the adhesion force at the droplet contact area tends to retard the initial spinning velocity, hence the droplet move with a reduced spinning velocity.

4.3 Numerical results

The droplet movement on an inclined hydrophobic wedge channel for various droplet sizes, inclination and wedge angles is examined numerically. The change in the adhesion force of the droplet on the different hydrophobic surface is represented by different contact angles in the simulation. The spinning motion of water droplet is predicted from a wedge form by two surfaces of different contact angles (145° and 160°) since previous studies show that the adhesion force needs to be overcome before the droplet is set to motion [63]. Therefore, the relative difference in the adhesion forces on the surfaces is predicted to create a difference in velocity which eventually leads to the spinning motion of the water droplet. In addition, liquid droplets on inclined surfaces undergo elastic deformation which is governed by the net force [63]. The translational linear velocity was predicted and measured from the analysis, experiment, and numerical simulations.

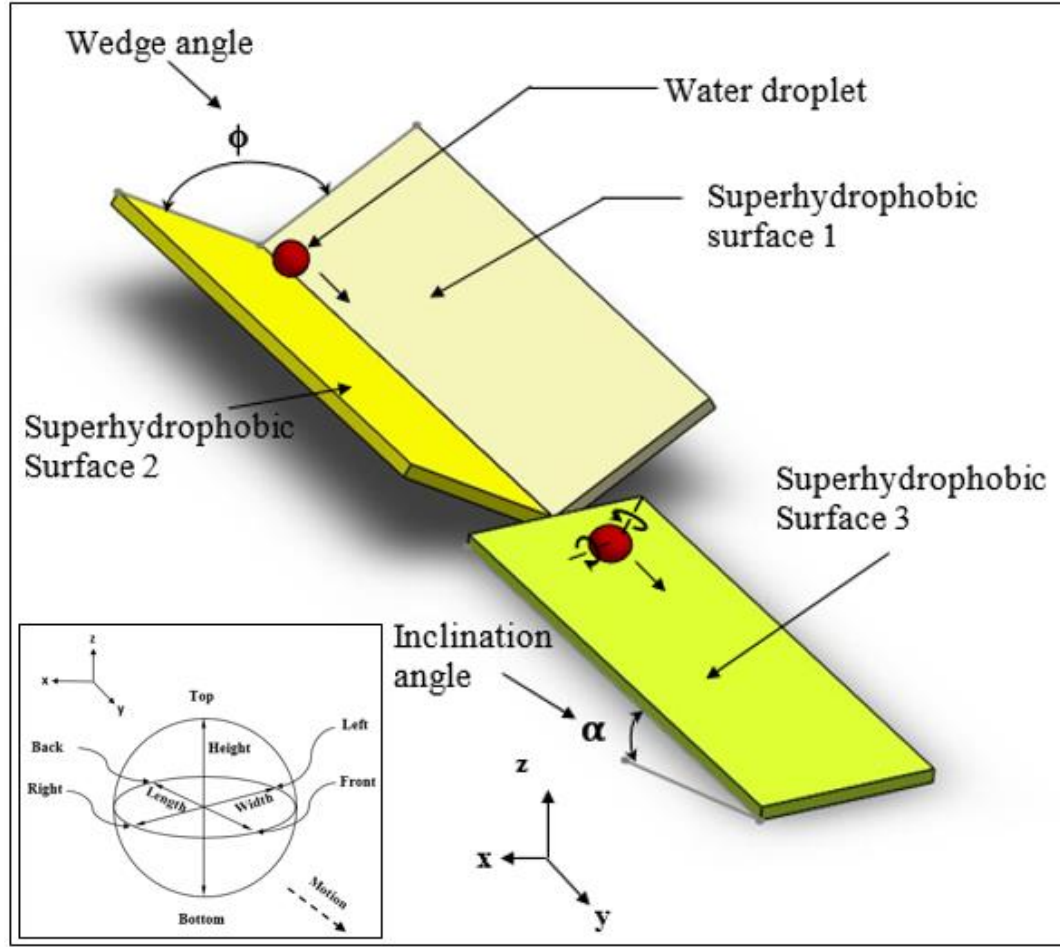


Figure 4.9: Water droplet dynamics on the wedged channel and flat surface and droplet geometry.

To study the velocity and pressure variation within the internal fluidity of the water droplet rolling off the inclined wedge, the height measured from bottom to top and the width measured from right to left and the length measure from the back to the front of the droplet are incorporated in the numerical simulation. To access the effect of contact angle on spinning velocity, two numerical models were created. In the first model, a numerical code for 20 μ L water droplet rolling off a 5 $^\circ$ inclined plane formed by two surfaces of 150 $^\circ$ contact angle each. In the second case, all parameters are kept similar to the first case only that the contact angles of the two surfaces are changed to 145 $^\circ$ and 160 $^\circ$. In the second

phase of the study, the dynamics of a water droplet was studied on flat surfaces. The second phase of the numerical study case also presented in two cases name as third and fourth case as shown in Figure 4.10 (c) and (d). In the third case, the motion of a $20\mu\text{L}$ water droplet on 5° flat inclined plane is simulated. While in the fourth case, an initial spin of 90rad/s is added to the droplet model similar to the 89.35° measure during experiments.

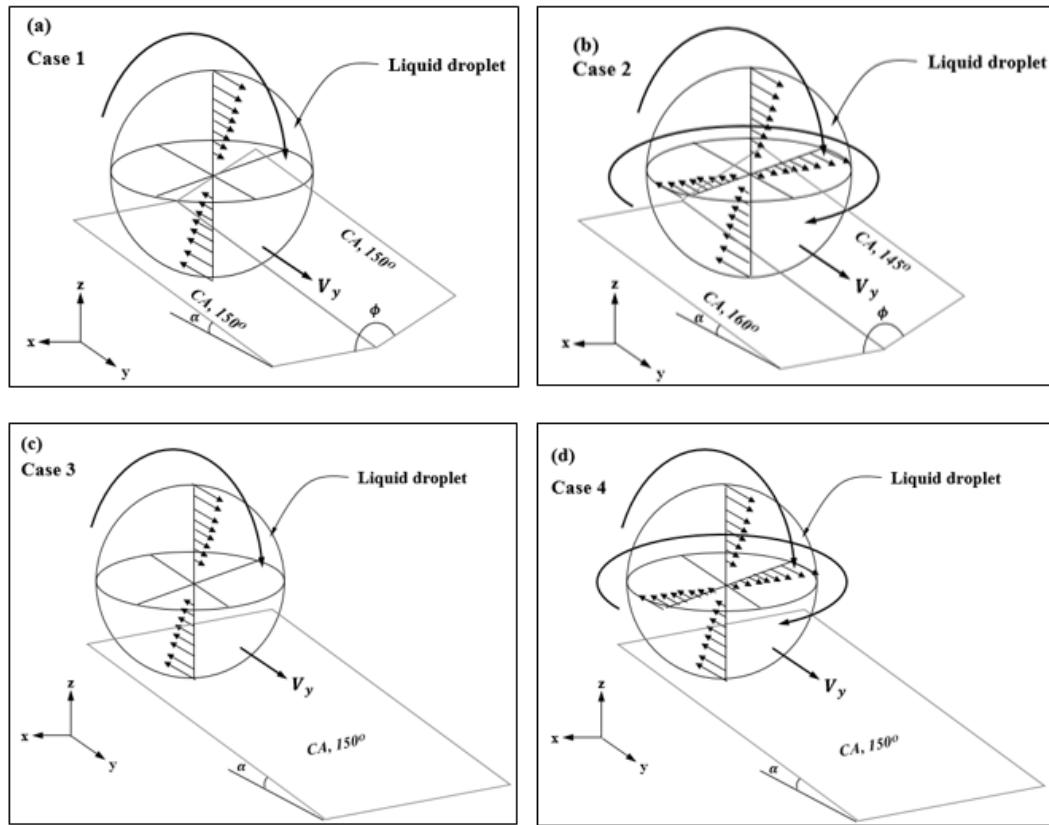


Figure 4.10: Cases considered in the numerical study

4.3.1 Contour plots for Velocity magnitude and Pressure – case 1

In the first case, dynamics of a water droplet on a wedge formed by two surfaces of 150° each is simulated. A time step of 0.02s is used to represent the velocity and pressure contours, while the time duration for droplet motion is 0.08s. To access changes in the magnitude of velocity and pressure across the water droplet three planes are cut. These planes are presented as x-y, y-z and x-z consisting the top view, side view and front view respectively. Figure 4.11 shows the velocity magnitude and pressure. The gauge pressure is used in the simulation since the pressure variation within the water droplet is negligible when compared to the absolute pressure value. More also, in each of the cut planes, a uniform range of pressure was applied which consist of the maximum and minimum values. The initial velocity of the droplet is set at 0 m/s since in the experiment stage the droplet was released from rest. Therefore, the velocity contour at 0.00s shows the minimum value in all the contour presented. As the water droplet propagates through the channel to 0.02s of from initial value, the height of the center of mass reduces this reduction of height makes the droplet elongates to form an oval shape. At this point, the surface tension force which determines the roundness of the water droplet tends to bring the droplet to the spherical shape while the retention force and gravitational forces act on the droplet. In the pressure plot of Figure 4.11, the pressure increases at the bottom of the water droplet in the regime when the droplet approaches an oval shape. When the water droplet passes from 0.02s to 0.04s the surface tension brings the center of mass higher while creating rotation and sliding velocity of the water droplet. During this regime, the pressure tends to reduce as shown in the pressure contour plot. The maximum and minimum height of the center of mass that creates the wobbling and puddling of water droplet diminishes with time as the

bond number associated with ω^2 increases. Velocity vector presented by a clockwise circulation reveals the rotational motion of the liquid droplet.

Y-Z plane (Side view)

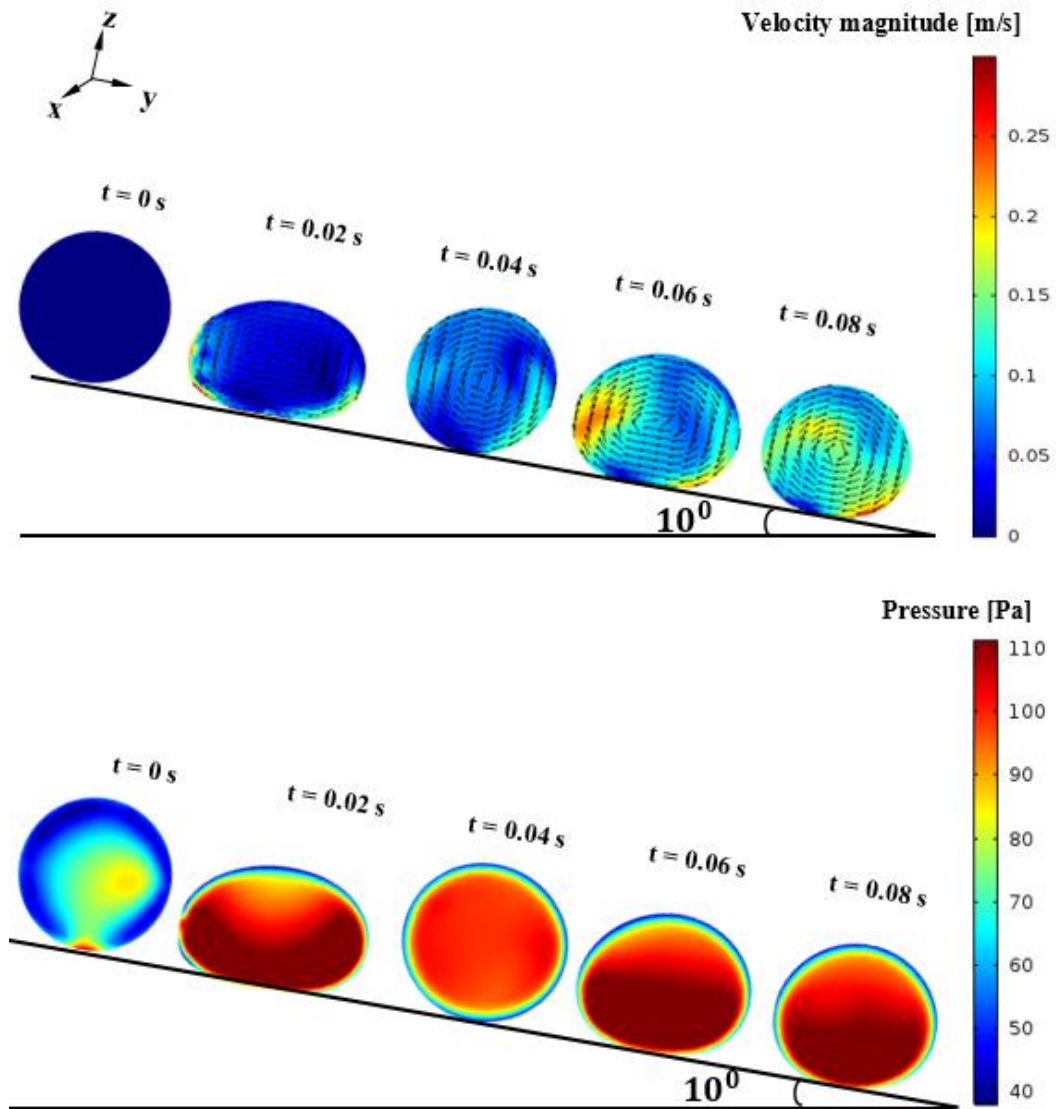


Figure 4.11: Side view of the velocity vector and pressure contour for a droplet on 150-150CA wedge.

X-Y plane (Top view)

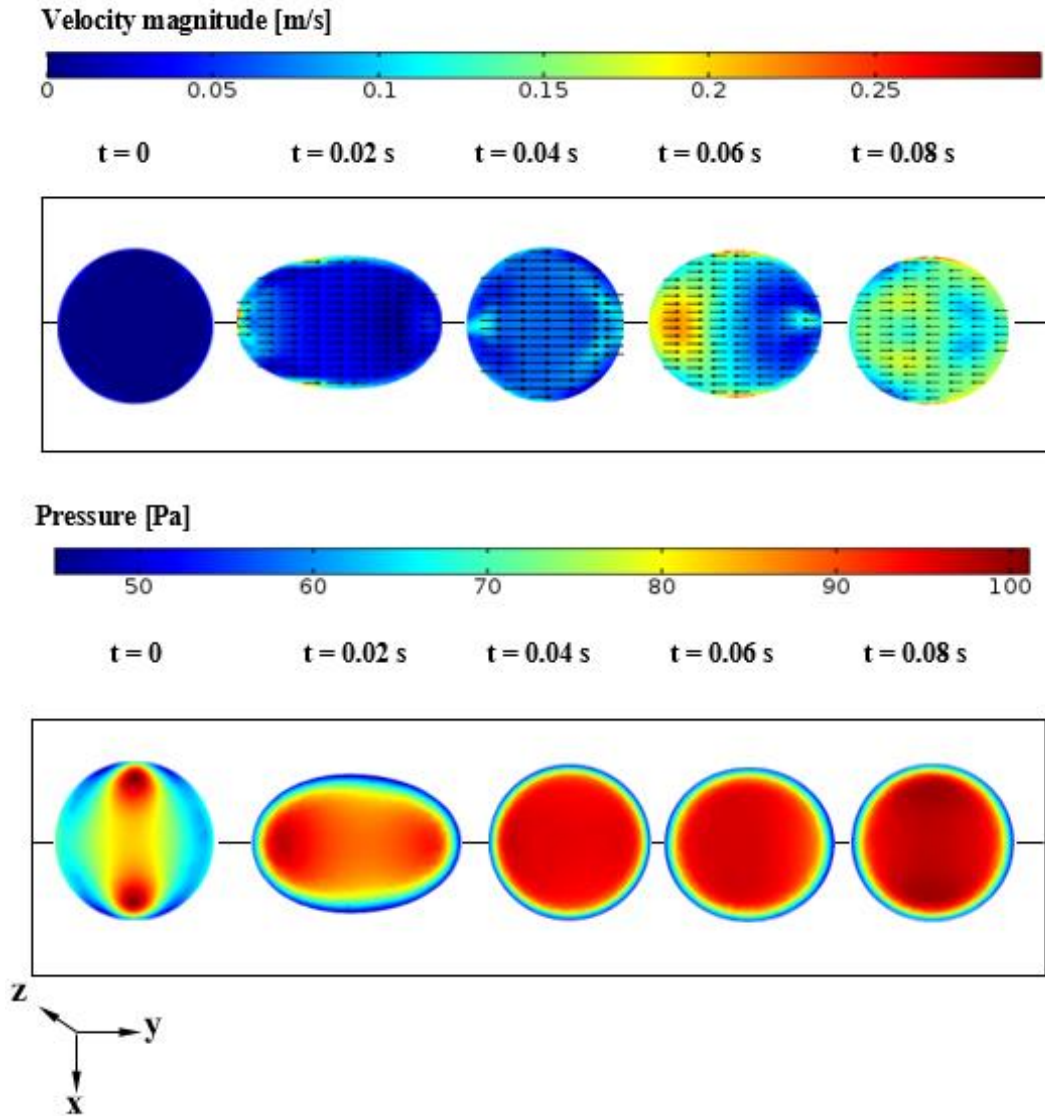


Figure 4.12: Top view of the velocity vector and pressure contour for a droplet on 150-150CA wedge.

Figure 4.12 shows the contours generated from the top cut plane. It is observed that the velocity magnitude along the length is higher at the back part of the droplet. This happens during the regime by which surface tension force tends to bring the water to the spherical shape, both the front and back sides of the water droplet move towards the center. Since

the gravitational force acts in the direction down the inclination, therefore the net tension force becomes more sensitive in the back of the water droplet thereby creating high internal velocity. The pressure contour of Figure 4.12 shows that from 0.04s to the subsequent times, the peripheral pressure gradient remains relatively constant. The velocity vector of the internal part of the droplet shows that the motion approaches center of the droplet from back and front. This is a clear picture of the effect of surface tension in trying to bring the droplet into a quasi-spherical shape. Both the velocity and pressure contours of Figure 4.10 shows lateral symmetry of water droplet moving on inclined wedge formed by two surfaces of the same properties.

In Figure 4.13, the vertically cut plane reveals the velocity and pressure gradient at the front of the droplet. Since the water droplet is constraint by the wedged surfaces, the wobbling and puddling motion is restricted. Hence, low velocity magnitude is observed in the velocity contour plot. The vector arrows indicated when the droplet is moving down and when surface tension force lift the water droplet. The pressure at the contact area is higher than in the other parts of the fluid. In the regime when the droplet has longer contact length, the internal pressure near the bottom part of the droplet attains the maximum value given as 100 Pa from pressure contour legend of Figure 4.13 up to almost half of the droplet volume.

Y-Z plane (Front view)

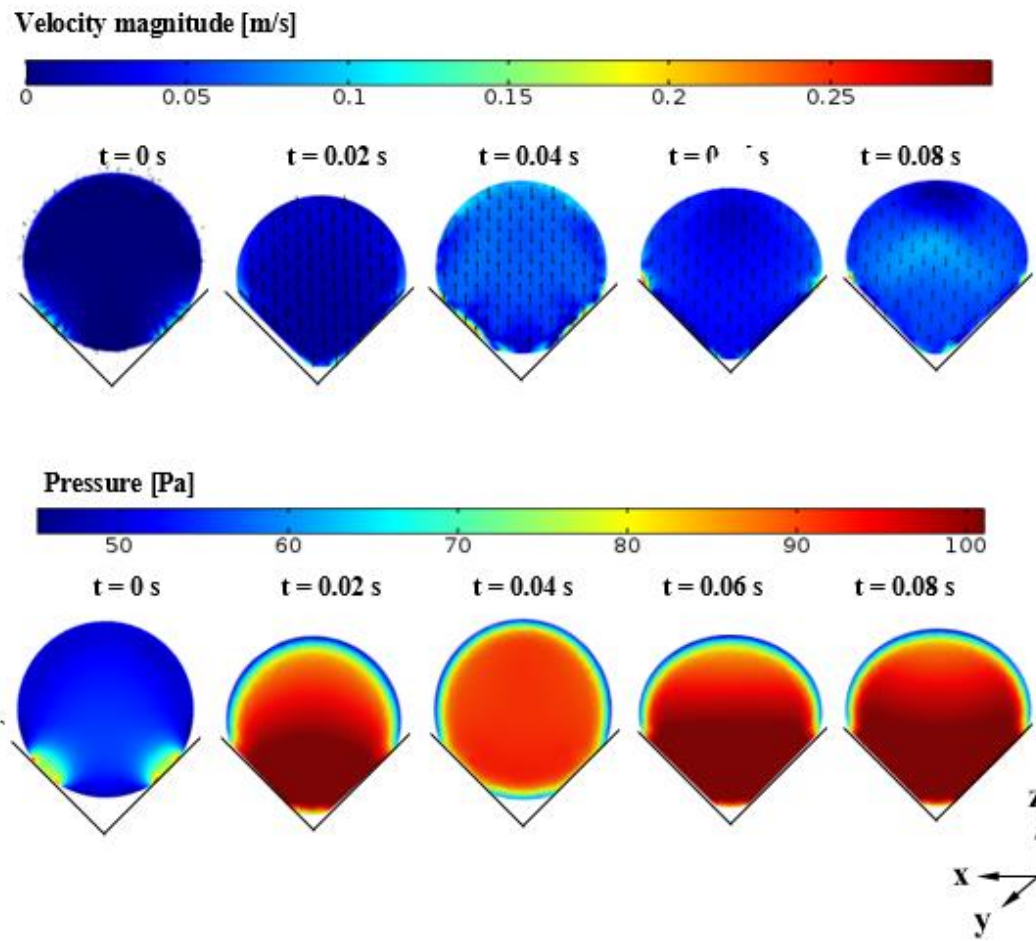


Figure 4.13: Front view of the velocity vector and pressure contour for a droplet on 150-150CA wedge.

4.3.2 Line plots for pressure and velocity magnitude

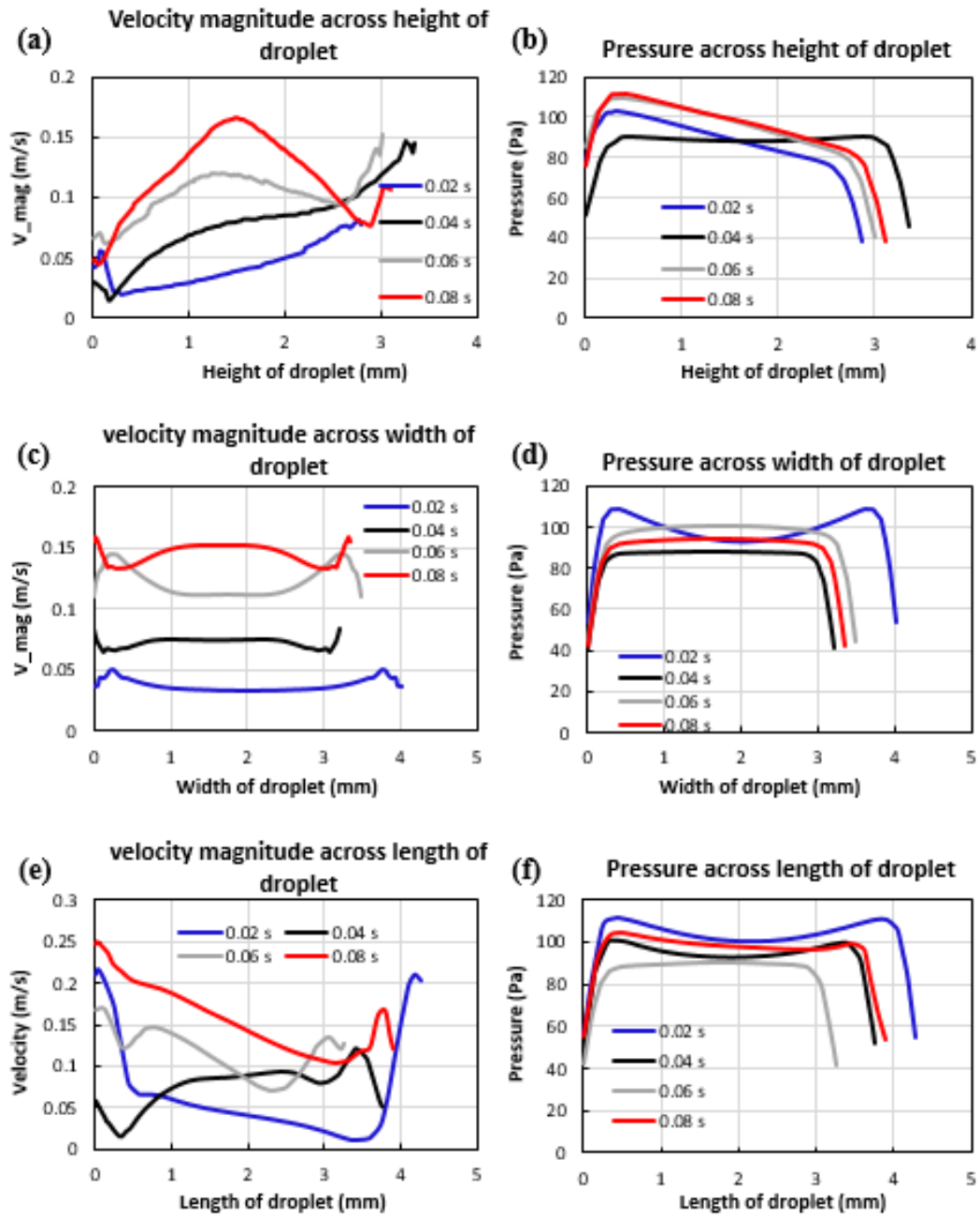


Figure 4.14: Line plots of pressure and velocity magnitude for a droplet on 150-150CA wedge at different time.

Three lines (height, width and length) defined in Figure 4.9(b) that describe the geometry of an elastically deformed water droplet are used to plot the pressure and velocity line charts.

In Figure 4.14 (a), as the water droplet reaches 0.02s of motion, the velocity gradient is created along the height of the droplet. This gradient increase continuously in all the time step of the droplet motion. However, at 0.08s the velocity magnitude along the height of the droplet decreases from the center to the top of the droplet. In the pressure contour plot of Figure 4.13 and pressure line plot of Figure 4.14, it is discovered that the pressure from the bottom of the droplet to the center is relatively high compare to under part of the droplet. Therefore, this phenomenon accounts for the fall in velocity magnitude from the center to the top of the water droplet. The gradient of velocity along the height of the droplet also creates a pressure gradient. However, the velocity gradient is positive while the pressure gradient is negative. In Figure 4.14 (c), the velocity magnitude along the width of the droplet shows that there is a continuous increase in magnitude from 0.02s to 0.08s but the velocity distribution remains symmetric throughout the flow regime. The pressure line plot of Figure 4.14 (d) shows that at 0.02s when the liquid droplet makes its first impact on the wedged channel the maximum pressure of 106 Pa exists near the contact area of the water droplet on the wedge channel. As the water droplet propagates through the channel, the pressure fluctuates in response to wobbling of the water droplet. Figure 4.14 (e) shows a velocity gradient along the length of the droplet from the rare to the front of the water droplet. A negative gradient reveals that the rotational motion of water droplet detaches the droplet contact with the hydrophobic surface from the rare part while the front part remains relatively at low motion.

4.3.3 Contour plots for Velocity magnitude and Pressure – case 2

Figure 4.15 shows the velocity magnitude and pressure contours at the side view cut via a lateral section. In this case, the water droplet is simulated on an inclined wedge formed by two surfaces of 145° and 160° contact angles. In the previous section, the wobbling and puddling motion of water droplet down the inclined wedge is discussed. The velocity contours of Figure 4.15 show an increment in magnitude especially when the water droplet propagate to about 0.04s to 0.06s during the flow regime. This is predicted to be the spinning effect which increases the total velocity magnitude. The velocity vectors indicated the rotation of the water droplet. The pressure contour of the rolling and spinning droplet does not change much from the previous section. However, there is a slight change in droplet shape and hysteresis. The change in the water droplet shape is due to the non-uniform contact line dynamics created by the two different surfaces of different contact angles. The 90° wedge channel constraints the droplet motion on the straight path. Considering that two surfaces of different contact angles created the platform upon which the water droplet spins, therefore a highly complex droplet behavior is expected.

In Figure 4.16 the top view of velocity and pressure contours are shown. As the water droplet starts to move, adhesion force in one part of the droplet contact exceeds the other part. In the part of droplet contact with adhesion force sliding speed becomes predominant and in the other part of the droplet, rolling exceed sliding. This difference in the adhesion force changes the flowing current within the internal fluidity of the water droplet. Spinning currents of varying degrees are generated in the water droplet as the motion propagates through the wedged channel. The pressure contour around the periphery of the water

droplet has no significant difference with the previous case. However, some random pressure changes that occurred are due to the spinning motion within the droplet.

Figure 4.17 shows the front view of the velocity and pressure contours during the motion of the water droplet. The difference in adhesion forces for the two surfaces leads to an asymmetrical positioning of the water droplet on the wedge. The droplet tends to attach more to the surface with a lower contact angle, thereby creating rotational current towards the lower contact angle surface. At 0.02s of the flow time, the droplet has the minimum height of center of mass, at this point the highest contact force exists, therefore very height spin and rotation velocity current are created. When the propagates, the maximum and minimum height of the center of mass is diminished due to the increase in the bond number [63]. Although different adhesion forces exist on the two surfaces of droplet contact, however, Pressure contour as shown in Figure 4.17 has not indicated any change in magnitude at the contact surfaces. This is because the larger contact area of the surface with low contact is not due to the water droplet dynamics but only due to surface property.

Y-Z plane (Side view)

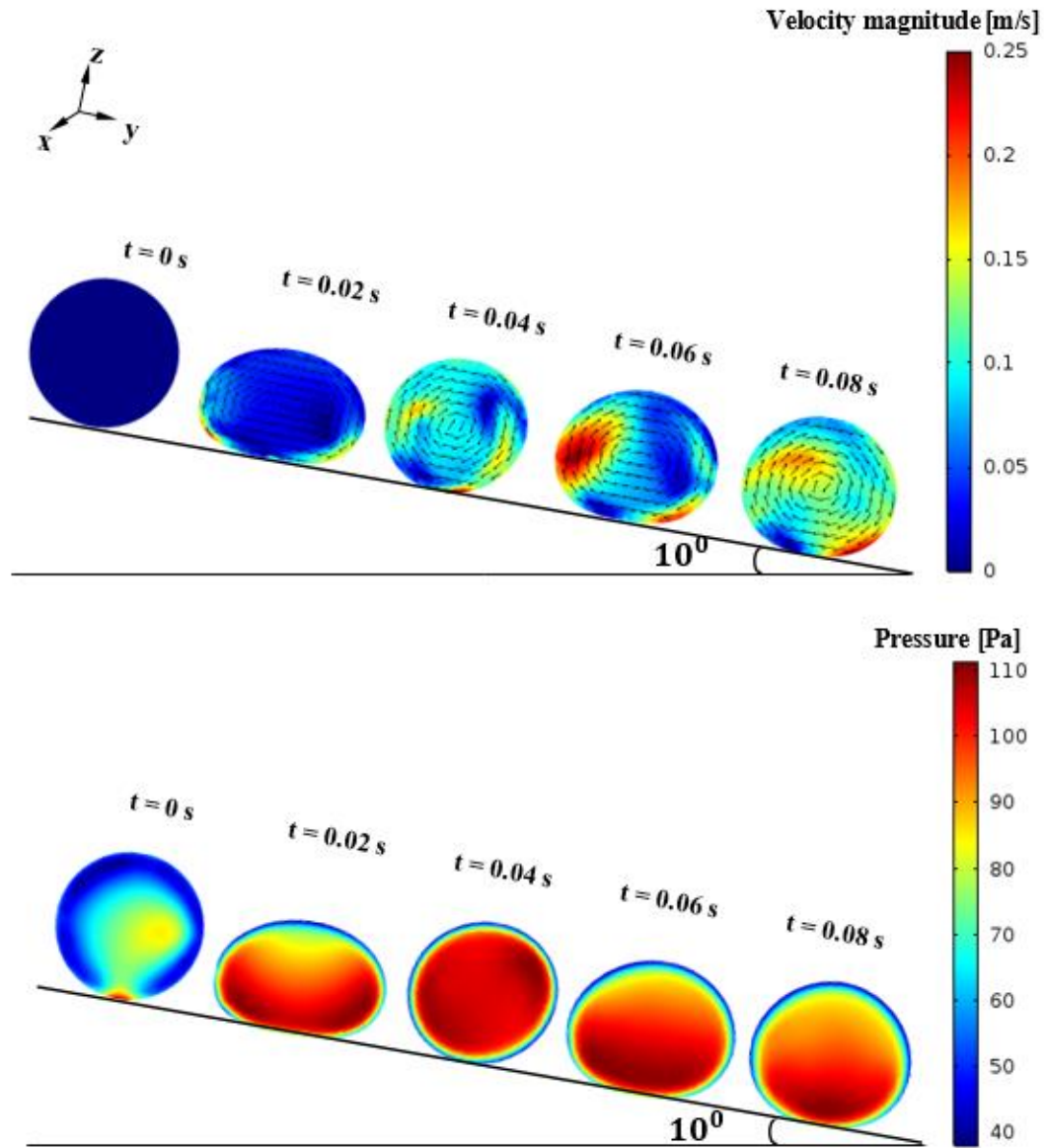


Figure 4.15: Side view of velocity vector and pressure contour for droplet on 145-160CA wedge.

X-Y plane

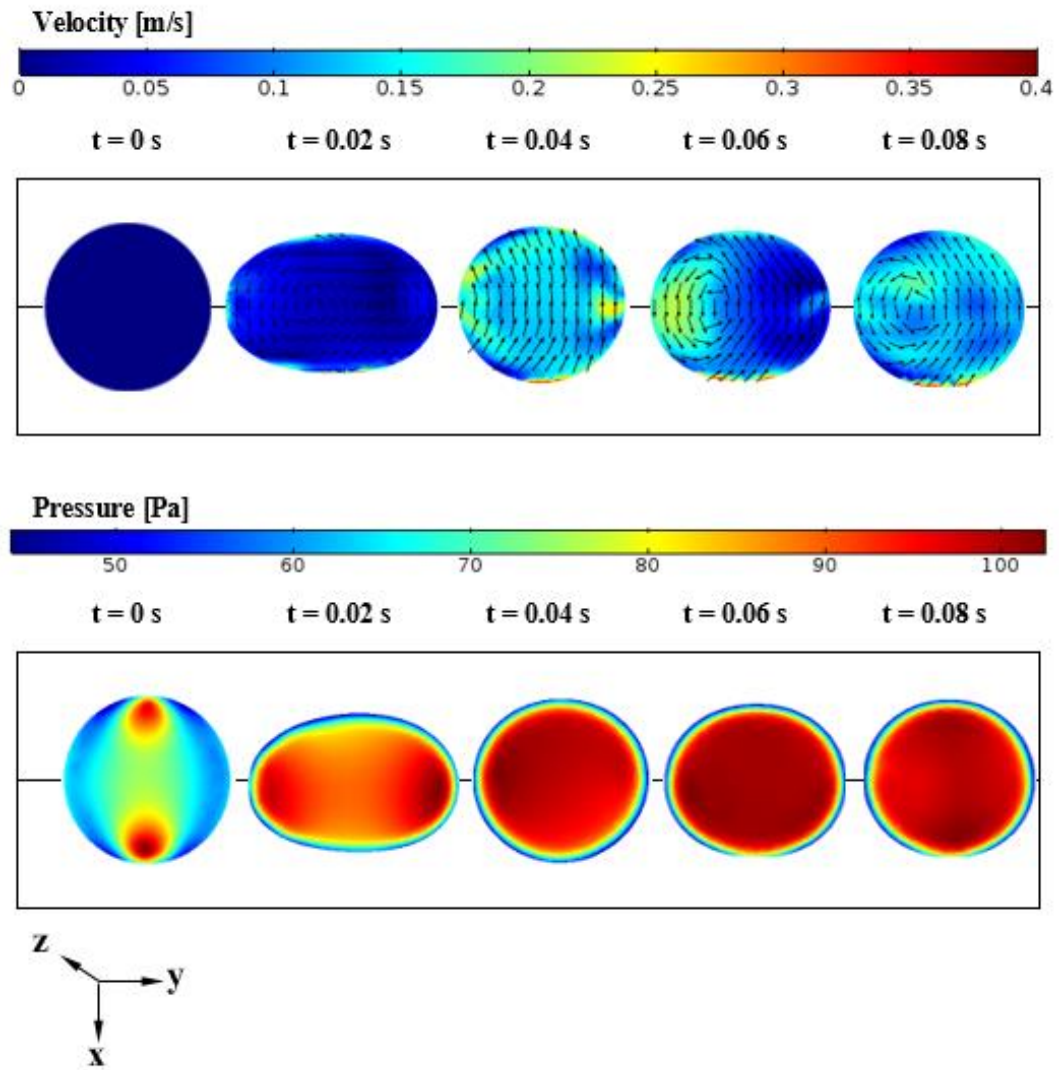


Figure 4.16: Top view of the velocity vector and pressure contour for a droplet on 145-160CA wedge.

Y-Z plane

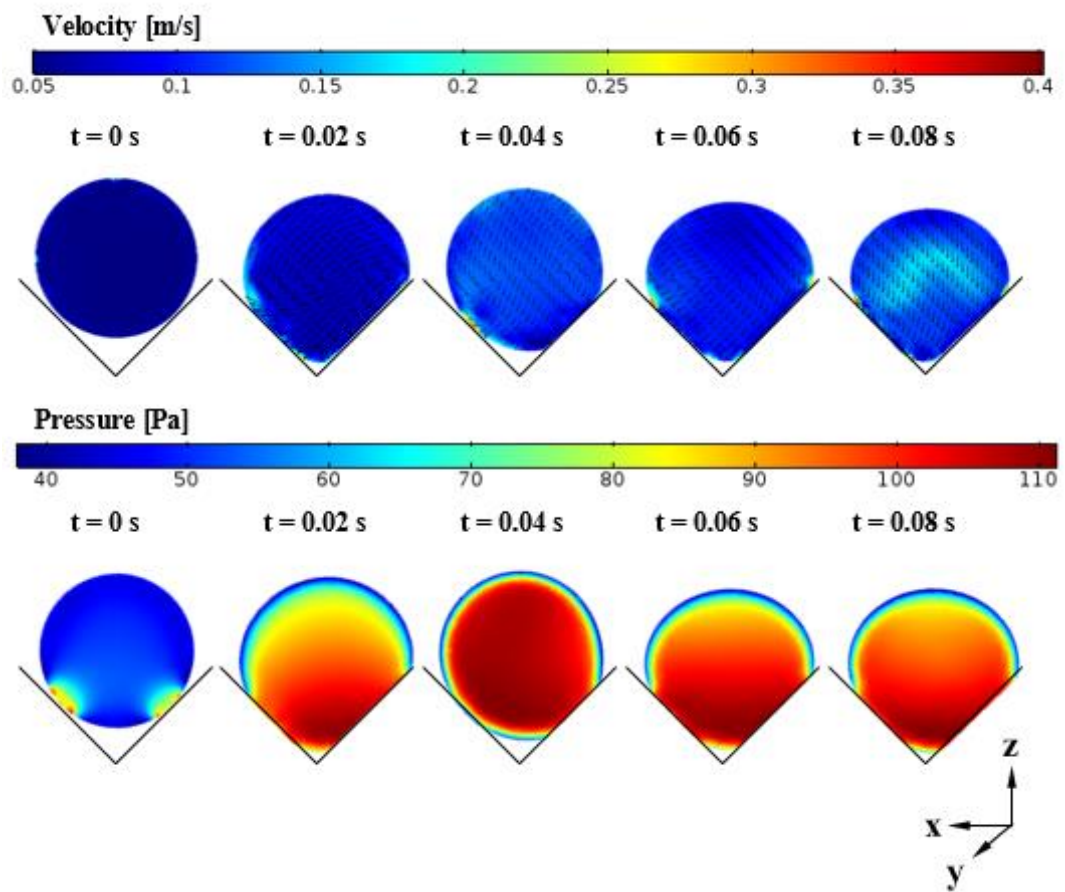


Figure 4.17: Front view of the velocity vector and pressure contour for a droplet on 145-160CA wedge.

4.3.4 Line plots for pressure and velocity magnitude

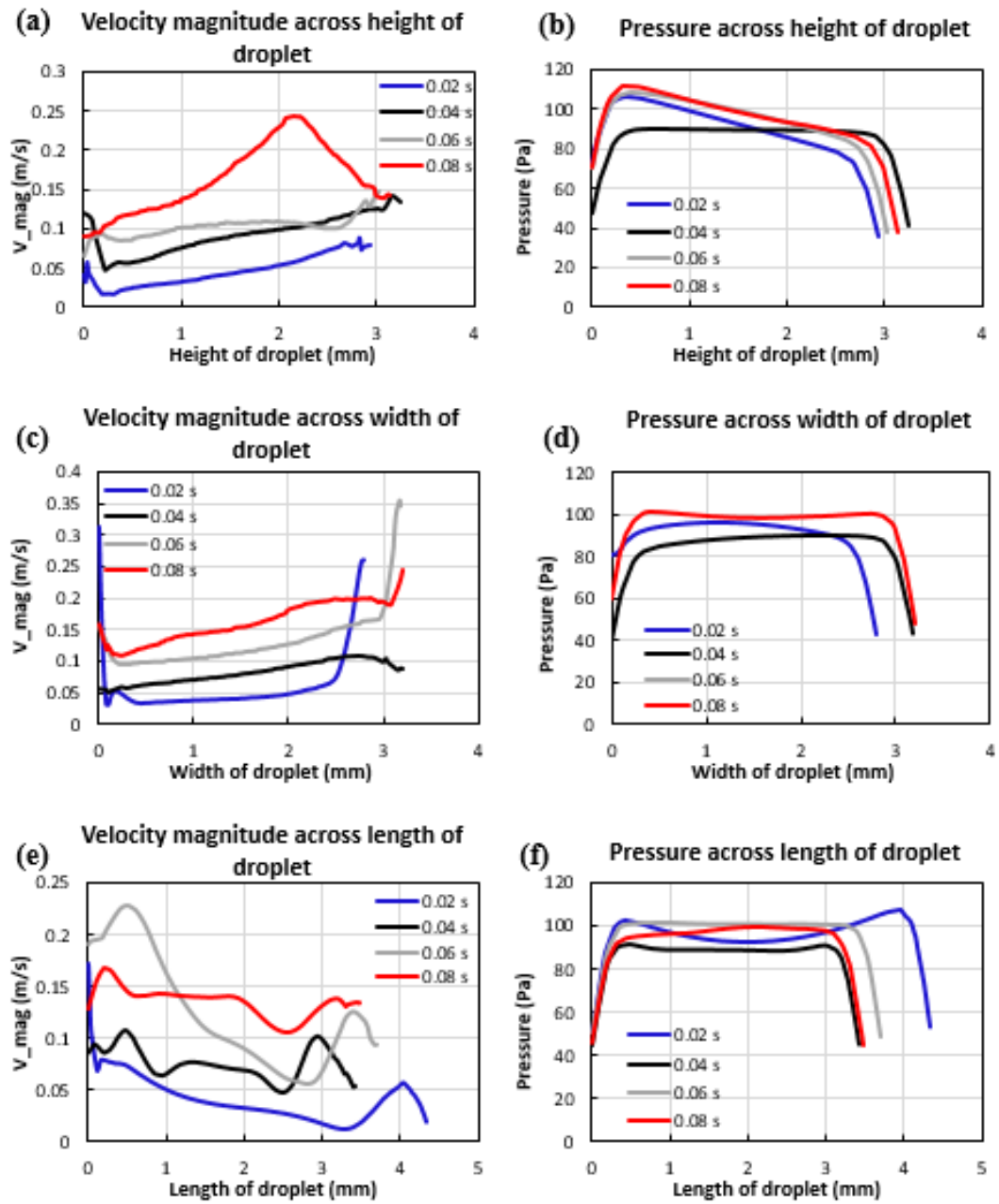


Figure 4.18: Line plots of pressure and velocity magnitude for droplet on 145-160CA wedge at different time.

Figure 4.18 shows the line plots of velocity magnitude and pressure across the height, width and length of the water droplet. The velocity magnitude along the height from bottom to top and the length from rear to the front of the water droplet provides an insight on the rotational velocity distribution within the internal fluidity of water droplet, while the velocity magnitude distribution along the width from right to left reveals spinning velocity created by the two surfaces of different contact angles. Figure 4.18 (a) shows a positive velocity gradient along the height of the droplet while Figure 4.18 (e) shows a negative gradient of the velocity magnitude along the length of the droplet from rear to front. Both plots indicate the rotational current across the internal fluidity of the water droplet. High rotational velocity current is created along the height of the droplet at 0.08 s of the flow time. This high current tends to diminish after a certain height above the droplet center of mass. This phenomenon was also discovered in the previous case for the motion of water droplet on wedge formed by two same contact angle (150°). In Figure 4.18 (e), the velocity distribution along the width from right to left of the water droplet is shown. The surface at the right side of the wedge has a high contact angle (160°), while the other surface at the left has a low contact angle (145°). The velocity within the internal fluidity of the water droplet shows a positive gradient from low contact angle surface to high contact angle surface. This gradient is observed to slightly increase with time from 0.02 s to 0.08 s as the droplet motion advances through the wedge. Therefore, a spinning current is generated across the width of the droplet. At 0.02 s and 0.06 s, sharp velocity gradient exists near the contact point of the water droplet. These are the regime at which the droplet center of mass is minimum and characterized by high pressure within the water droplet and high sliding velocity at the high contact angle surface.

4.3.5 Average spinning and rotation angular velocity

Water droplet motion between two surfaces of different contact angle (145° and 160°) has a spinning and rotation velocities within the internal flow field. The magnitude of the flow velocity and the average droplet radius is used to compute the spinning and rotational angular velocities of the water droplet. Figure 4.19 shows the variation of both spinning and rotation angular velocities of the water droplet. Figure 4.19 shows the variation of both spinning and rotation angular velocity at 0.02 s, 0.04 s, 0.06 s, and 0.08 s during the droplet flow regimes.

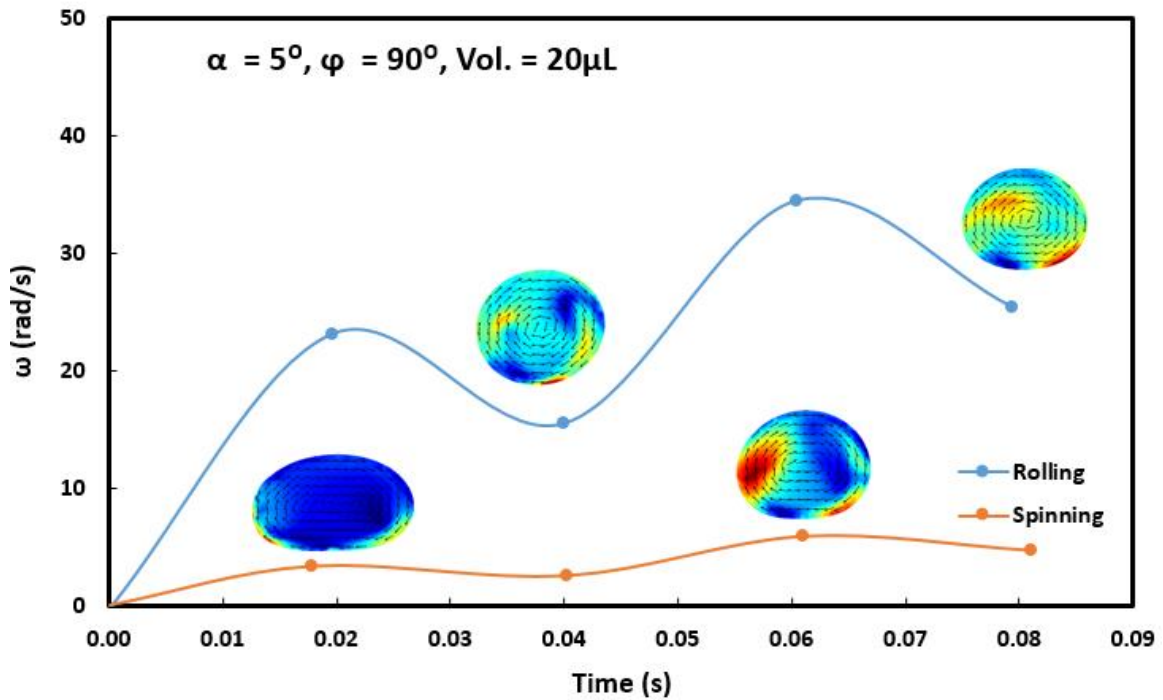


Figure 4.19: Spinning and rotation angular velocity

The motion of water droplet is characterized by wobbling and puddling nature depending on the net force within the line of flow of the droplet. The contact line dynamics and contact angle hysteresis determined the roundness of liquid droplet. In Figure 4.19, the average

value of the spinning and rotation velocity is determined at four flow times (0.02 s, 0.04 s, 0.06 s, and 0.08 s) in the water droplet simulation. At 0.02 s, the water droplet has the first contact with the surfaces. At this point, a gradient of velocity is created along the height and width of the droplet which generates the first circulation current of rotation and spinning velocity. As the motion advances to 0.04 s, a fall in other both velocities observed, which is due to the rise in the center of mass which reduces the contact pressure of the droplet on the surface. The second regime of the high value of rotational and spinning angular velocity occurred when the droplet center of mass moves to the next minimum value around 0.06 s. At this point, the maximum value is recorded for spinning and rotation angular velocity given as 32rad/s and 44.8 rad/s. Another reduction in the flow field velocities is observed at 0.08 s when the droplet center of mass rises.

Water droplet dynamic motion made all the measurable quantities to fluctuate with time during the wobbling and puddling of the water droplet. As the rotational angular velocity of the droplet increase, the rotational bond number also rises in the order of ω^2 . This larger the magnitude of the rotational bond number, the more the stability of the center of mass of the water droplet.

4.3.6 Cleaning efficiency

The cleaning efficiency is investigated for a rolling droplet and the water droplet that spins while rolling. The low surface energy plane has created the dust picking ability of the droplet without wetting the contact area. The wobbling of a rolling droplet is as a result of the constant fluctuation of surface adhesion energy is affected the motion stability.

Therefore, a striation-like pattern of a clean path is observed for the rolling droplet as shown in Figure 4.20a. While in the case of a rolling and sliding droplet, the high rotation speed created from rolling and spinning components led to a high rotational bond number which enhanced the stability of the water droplet. Such increased stability creates a relatively stable contact area dynamic which results in a straight cleaned pattern as shown in Figure 4.20b.

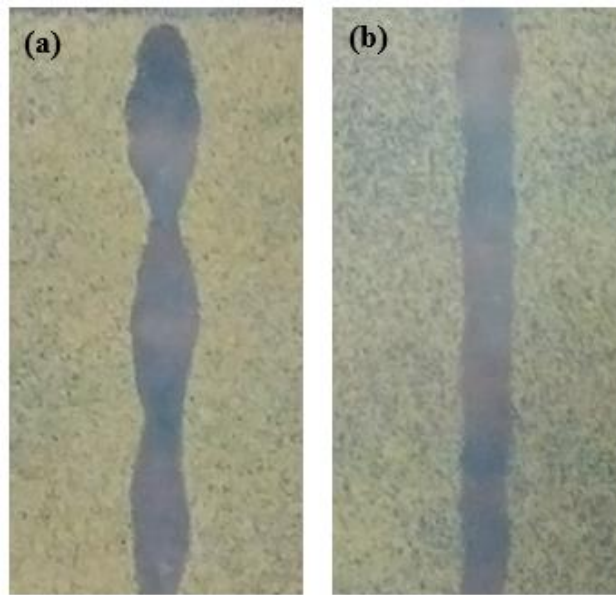


Figure 4.20: Area cleaned (a) by rolling droplet (b) by spinning and rolling droplet

The overall area cleaned by the rolling and spinning droplet is expressed as the total cleaned area. The total cleaned area is used to normalize the area clean by the water droplet that only rolls off the dusty inclined surface. The dimensionless area is determined from 0ms to 100ms of the droplet motion time as shown in Figure 4.21. The striation-like motion of the rolling droplet results in a wavy-like chart pattern and has negatively affected the dust cleaning efficiency. Base on the selected time frame of the study, the efficiency of the

rolling droplet has reduced to about 87% of the cleaning efficiency of the droplet that rolls and spins. Also, the wobbling of rolling droplet makes it difficult to obtain a straight cleaning path. This makes it difficult to predict the amount of water droplets needed to clean a desired dusty area. The concentration of dust per unit area on the inclined surface also places a significant role in the dust cleaning pattern. In a highly dusty surface, the mass of the liquid droplet and the surface tension changed rapidly and the length of the droplet is elongated while the width is narrowed followed by drying off of the rolling droplet. This phenomenon affected the cleaning efficiency of both rolling droplet and the droplet that spins and rolls, thereby making the contact area dynamics not significant in predicting the dust cleaning performance. Therefore, in a frequently dusty environment to predict the droplet dynamics on cleaning efficiency, more frequent surface cleaning is required.

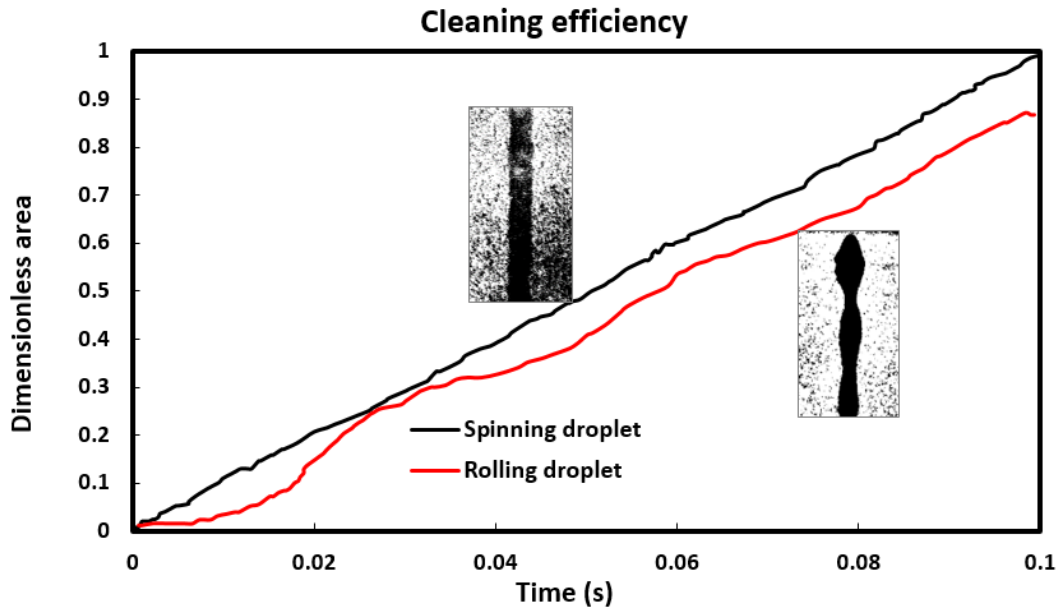


Figure 4.21: Dust cleaning efficiency

CHAPTER 5

CONCLUSION

Understanding the nature of dynamic behavior of water droplet with respect to dust particle removal in an incline superhydrophobic surface becomes necessary. In this study, a coating technique is developed to hydrophobize the surface. The rotation and spinning motions of a water droplet with respect to the variation of inclination of the non-parallel surfaces (wedges) of the hydrophobic walls is studied analytically, experimentally and numerically. Considering liquid droplet motion on inclined wedge channel, an ordinary differential equation is analytically derived and solved. The analytical results provide the platform upon which the experimental method is designed and the effect of various parameters in the analytical model is discussed. The rotational and spinning velocity of the liquid droplet in the analytical model accounts for the effect of droplet sizes, surface energy, channel and inclination angles. Both analytical and experimental approaches provide validation and a clear path on the effect of parameters under study. However, velocity and pressure within the internal fluidity as well as the contact line dynamics which determines the dust cleaning ability of the water droplet are studied in a numerical simulation. The commercial code for the Conservative Level set method is adopted to simulate droplet dynamics on an inclined wedged channel with different hydrophobic properties in the version 5.3a COMSOL Multiphysics software. The level set parameter which controls the interfacial thickness was set to the default value, while the maximum flow velocity derived experimentally as 0.51 m/s was used as the reinitialization parameter. The model accounts for the effect of contact angle in droplet simulations and captured the droplet contact line dynamics and

translational linear velocity with about 95% accuracy as determined from a validation study.

The numerical study is divided into two cases. In the first case of the simulation, water droplet motion on a wedge formed by hydrophobic surfaces of similar contact angle (150° each) is studied, while in the second case, the two surfaces have different contact angles (145° and 160°). As the liquid droplet propagates through the inclined channel, the surface tension force, gravitational force, adhesion force and drag force all resulted to a net force that sets the water droplet into wobbling and puddling motions which affect the roundness of the droplet and sets the center of mass into continuous fluctuation. The pressure increases at the bottom of the water droplet in the regime when the droplet approaches an oval shape. As the water droplet passes from 0.02 s to 0.04 s the surface tension brings the center of mass higher towards centroidal point of the droplet while creating rotation and sliding velocity of the water droplet. During this regime, the pressure tends to reduce as observed from the pressure contour plot. The maximum and minimum height of the center of mass that creates the wobbling and puddling of water droplet diminishes with time as the bond number associated with increases. As the center of mass approaches the minimum height, the spinning and rotation angular velocities tend to increase in magnitude due to an increase in the contact pressure. As the center of mass move to the maximum height, both spinning and rotational velocities fall to lower values. The maximum values of rotation and spinning angular velocity in the simulation are predicted as 34.4 rad/s and 6 rad/s from 0 to 0.08s of simulation time. The dust cleaning efficiency of the water droplet has shown that there is a reduction in efficiency to 87% if the droplet only rolls on the dusty surface due to the striation pattern caused by the wobbling nature of the rolling droplet.

The droplet cleaning efficiency is enhanced by 98% when the droplet is set to roll and spin on the dusty hydrophobic surface. This is mainly due to the ability of the spinning droplet to maintain a relatively constant wetting diameter in the droplet path and thereby reducing the striation-like effect created by a water droplet that only rolls on an inclined hydrophobic surface. The stability of a liquid droplet rolling is enhanced when the overall rotational speed increases and thus the spinning motion has provided a means of enhancing the overall rotational motion of the droplet without the need of any external force.

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APPENDIX

Table-A1: Experimentally determined contact angles and wetting radius

$\alpha = 5^\circ$												
Time (s)	20 μ L			30 μ L			40 μ L			50 μ L		
	θ_A	θ_R	$R_h(m)$	θ_A	θ_R	R_h	θ_A	θ_R	R_h	θ_A	θ_R	R_h
0	151	142	0.00164	154	145	0.00188	156	145	0.00198	153	145	0.00211
0.05	144	141	0.00152	148	141	0.00169	147	136	0.00181	155	142	0.00198
0.1	154	146	0.00161	155	143	0.00185	150	143	0.00201	152	141	0.00209
Average	150	143	0.00159	152	143	0.00181	151	141	0.00193	153	143	0.00206
$\alpha = 10^\circ$												
Time (s)	20 μ L			30 μ L			40 μ L			50 μ L		
	θ_A	θ_R	R_h	θ_A	θ_R	R_h	θ_A	θ_R	R_h	θ_A	θ_R	R_h
0	153	138	0.00164	155	141	0.00195	152	137	0.00207	154	135	0.00215
0.05	148	142	0.00156	147	135	0.00172	148	133	0.00186	151	132	0.00199
0.1	151	136	0.00161	156	134	0.00185	156	132	0.00209	156	136	0.00214
Average	151	139	0.00160	153	137	0.00184	152	134	0.00201	154	134	0.00209

$\alpha = 15^\circ$												
Time (s)	20 μ L			30 μ L			40 μ L			50 μ L		
	θ_A	θ_R	R_h	θ_A	θ_R	R_h	θ_A	θ_R	R_h	θ_A	θ_R	R_h
0	157	134	0.00165	152	132	0.00189	149	131	0.00203	150	132	0.00214
0.05	146	136	0.00151	154	134	0.00177	156	127	0.00189	158	135	0.00201
0.1	153	137	0.00162	154	129	0.00181	155	129	0.00197	156	131	0.00221
Average	152	136	0.00159	153	132	0.00182	153	129	0.00196	155	133	0.00212

In Table-A1, effect of droplet size and motion time on the contact angle and droplet average radius of liquid droplet is investigated experimentally. This values were used to compute droplet angular velocity down the inclined wedged channel.

Rotational and sliding velocities

Effect of Volumes (20 μ L, 30 μ L, 4 μ L and 50 μ L)

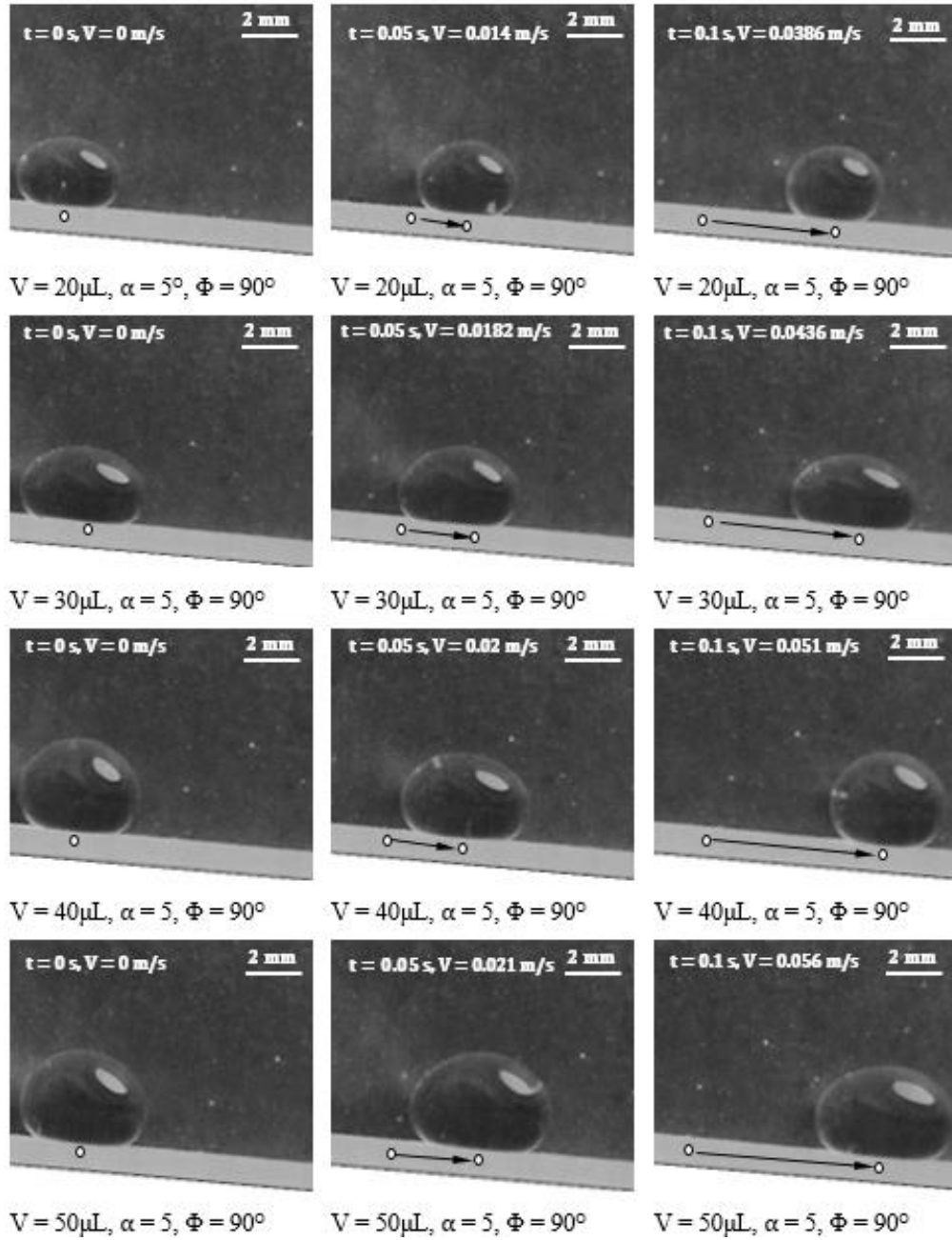


Figure-A1: Effect of droplet size on translational velocity.

Effect of Inclination angle (5° , 10° , and 15°)

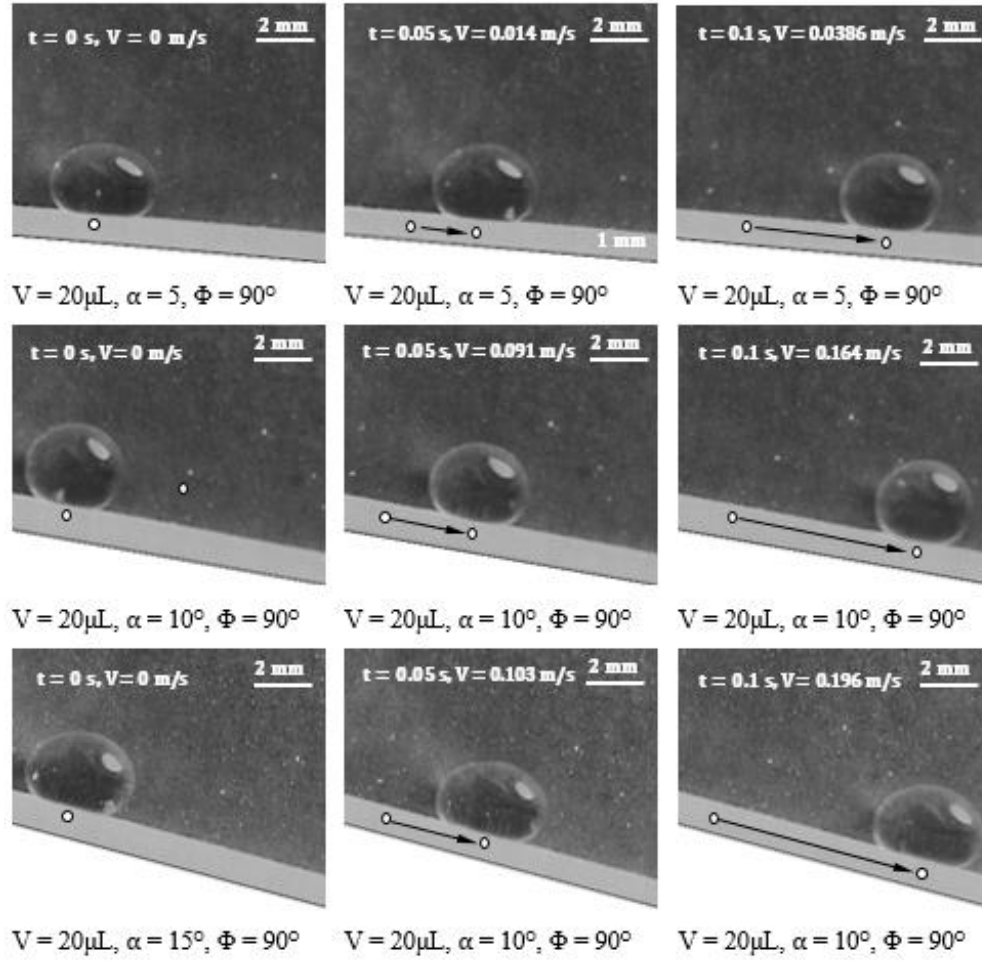


Figure-A2: Effect of plane inclination angle on translational velocity.

Effect of Wedge angle; 90°, 110°, 130° and 150°

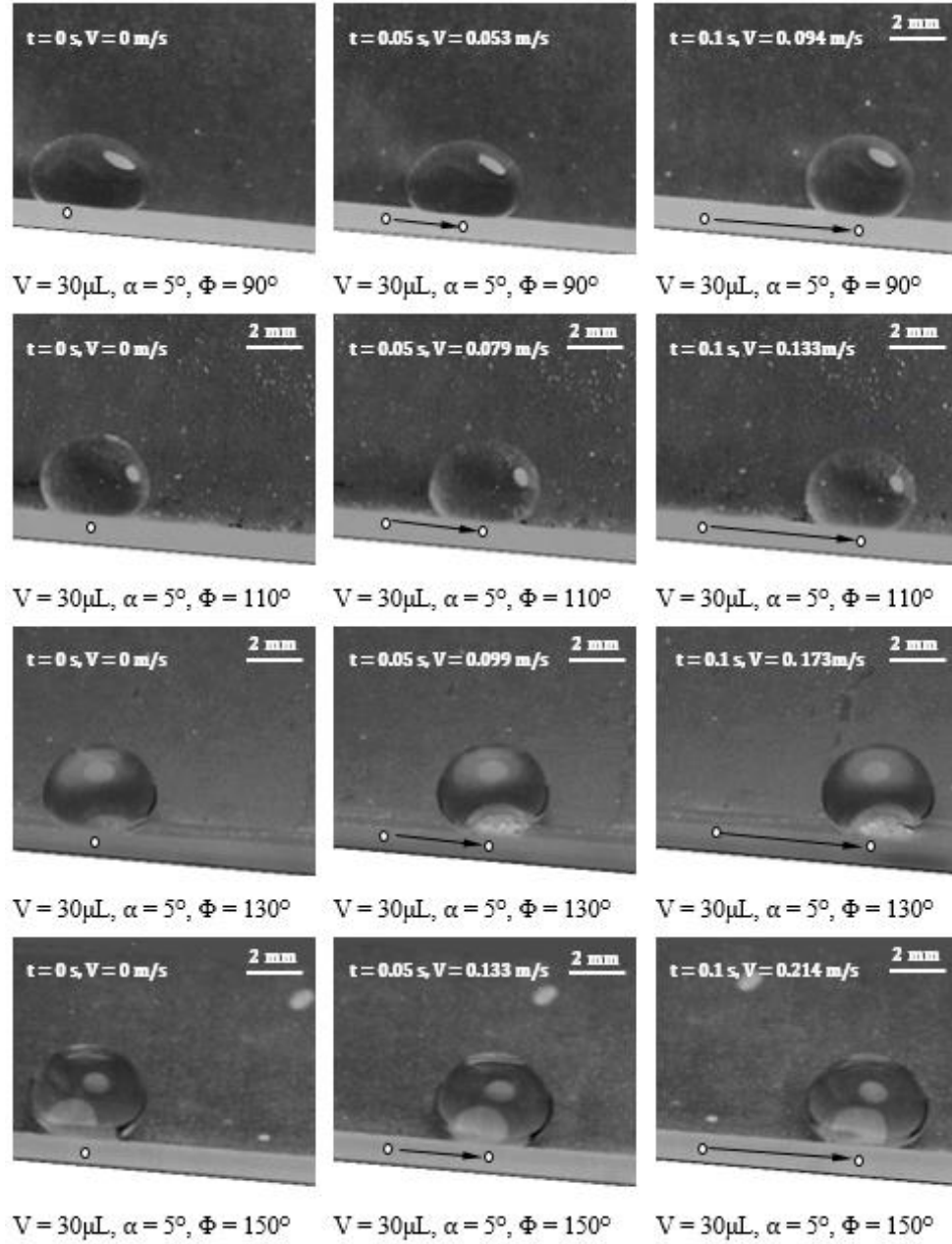


Figure-A3: Effect of wedge angle on translational velocity.

Rotational velocity

Effect of volume on rotational velocity

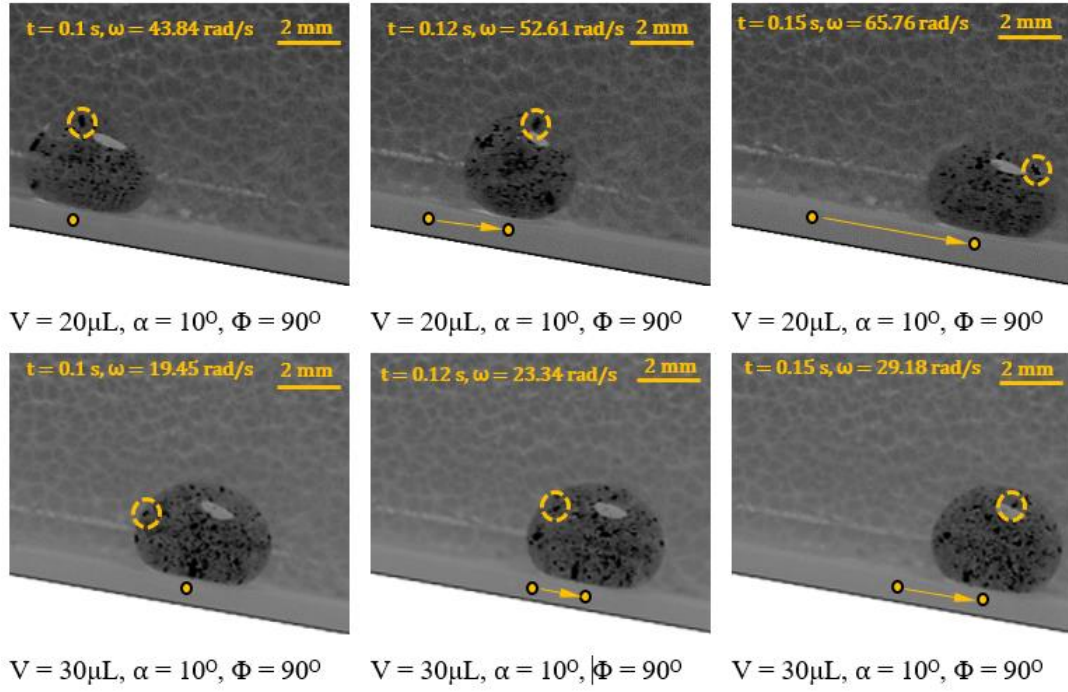


Figure-A4: Effect of droplet size on the rotational linear velocity

Effect of inclination on rotational speed

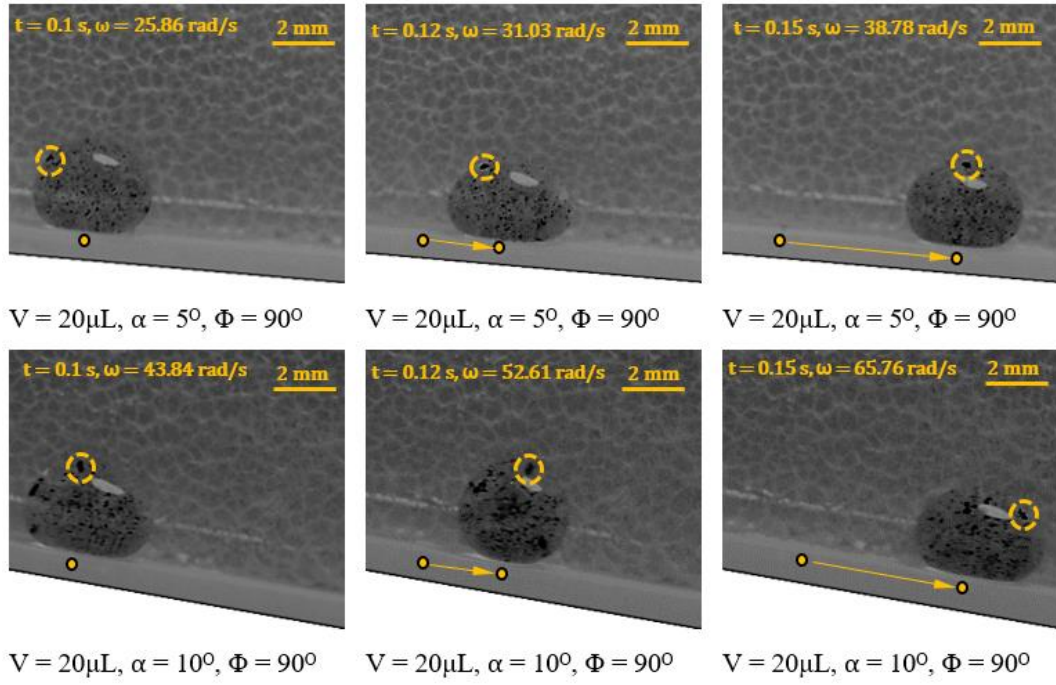


Figure-A5: Effect of plane inclination on the rotational linear velocity

Effect of wedge on rotational velocity

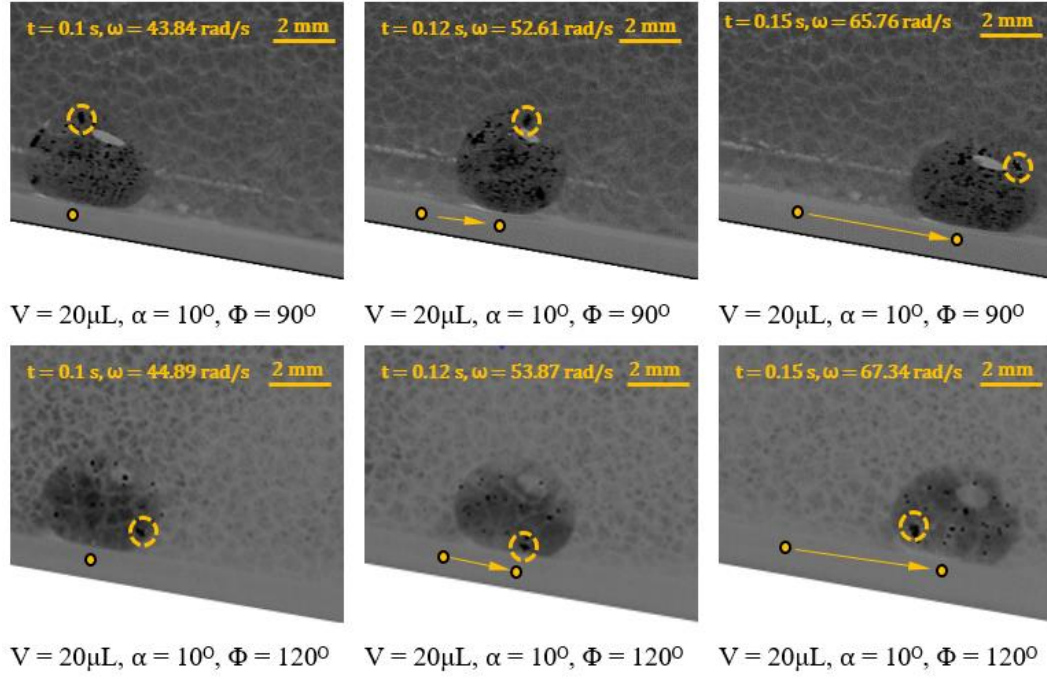


Figure-A6: Effect of plane inclination on the rotational linear velocity

Spinning velocity

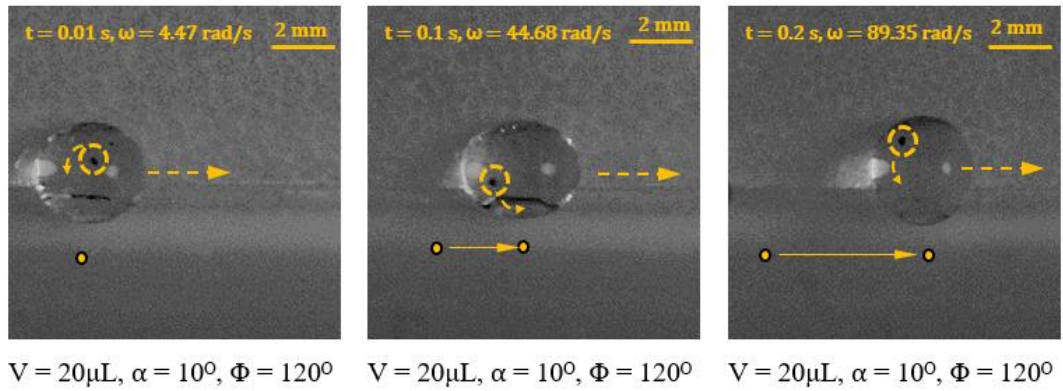


Figure-A7: spinning velocity of 20μL water droplet

Three-Dimensional Contour plots

Lateral view of Internal fluidic velocity for rolling droplet on inclined wedged channel

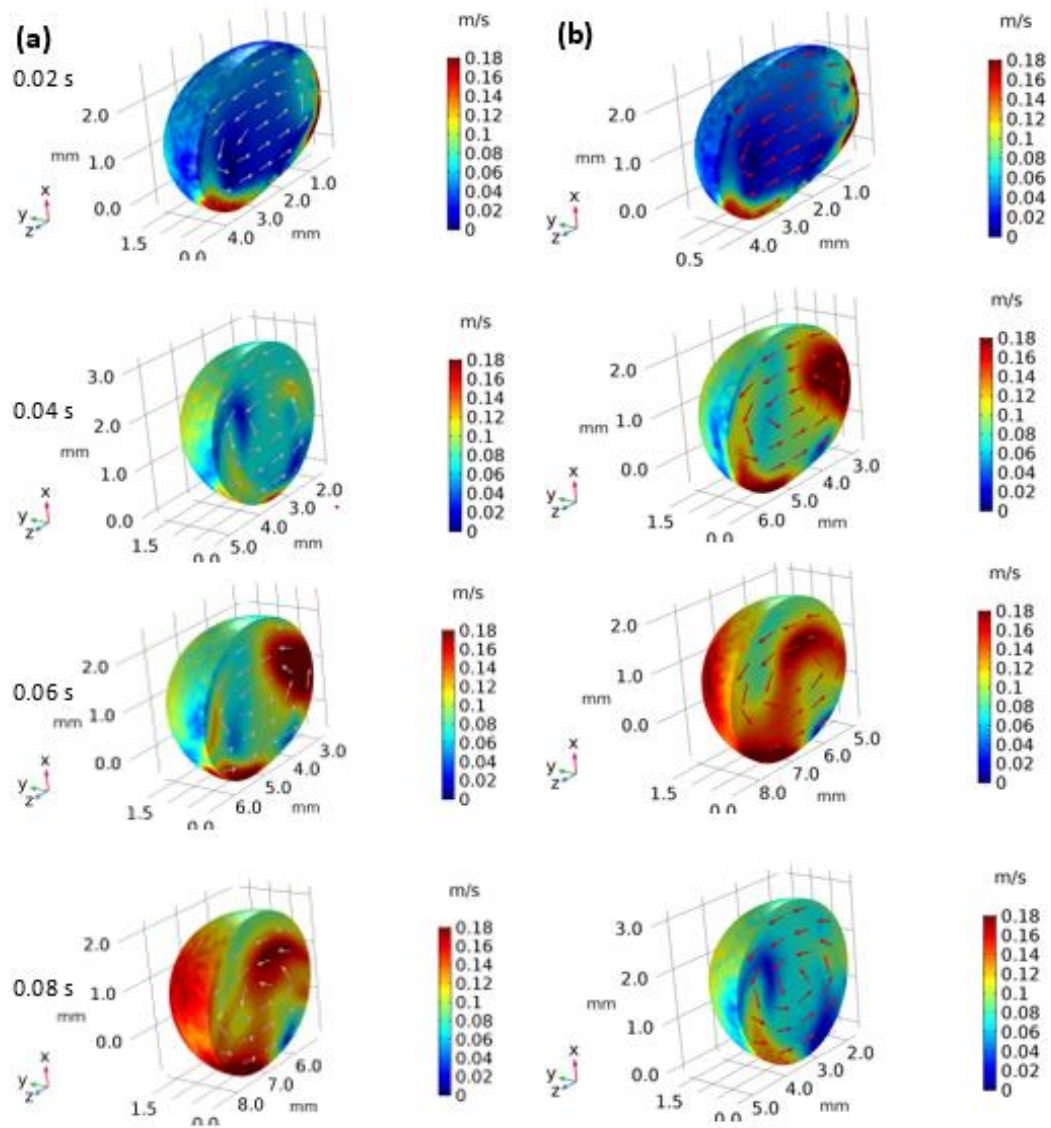


Figure-A8: Droplet rolling behavior down an inclined wedged hydrophobic channel for: (a) 145°-160° and (b) 150°-150° contact angles

Vertical view of Internal fluidic velocity for rolling droplet on inclined wedged channel

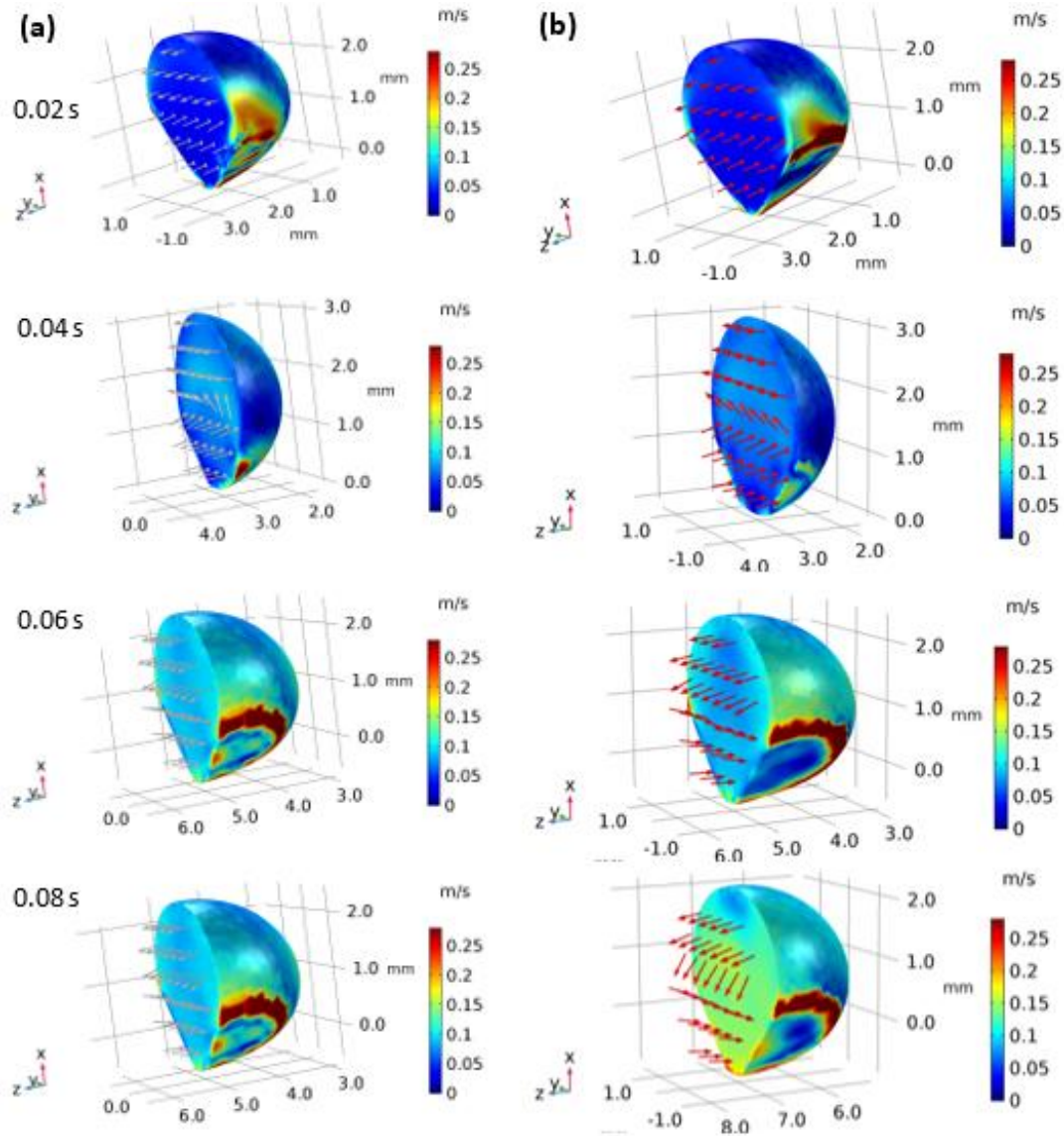


Figure-A9: Droplet rolling behavior down an inclined wedged hydrophobic channel for: (a) 145°-160° and
(b) 150°-150° contact angles

Horizontal view of Internal fluidic velocity for rolling droplet on inclined wedged channel

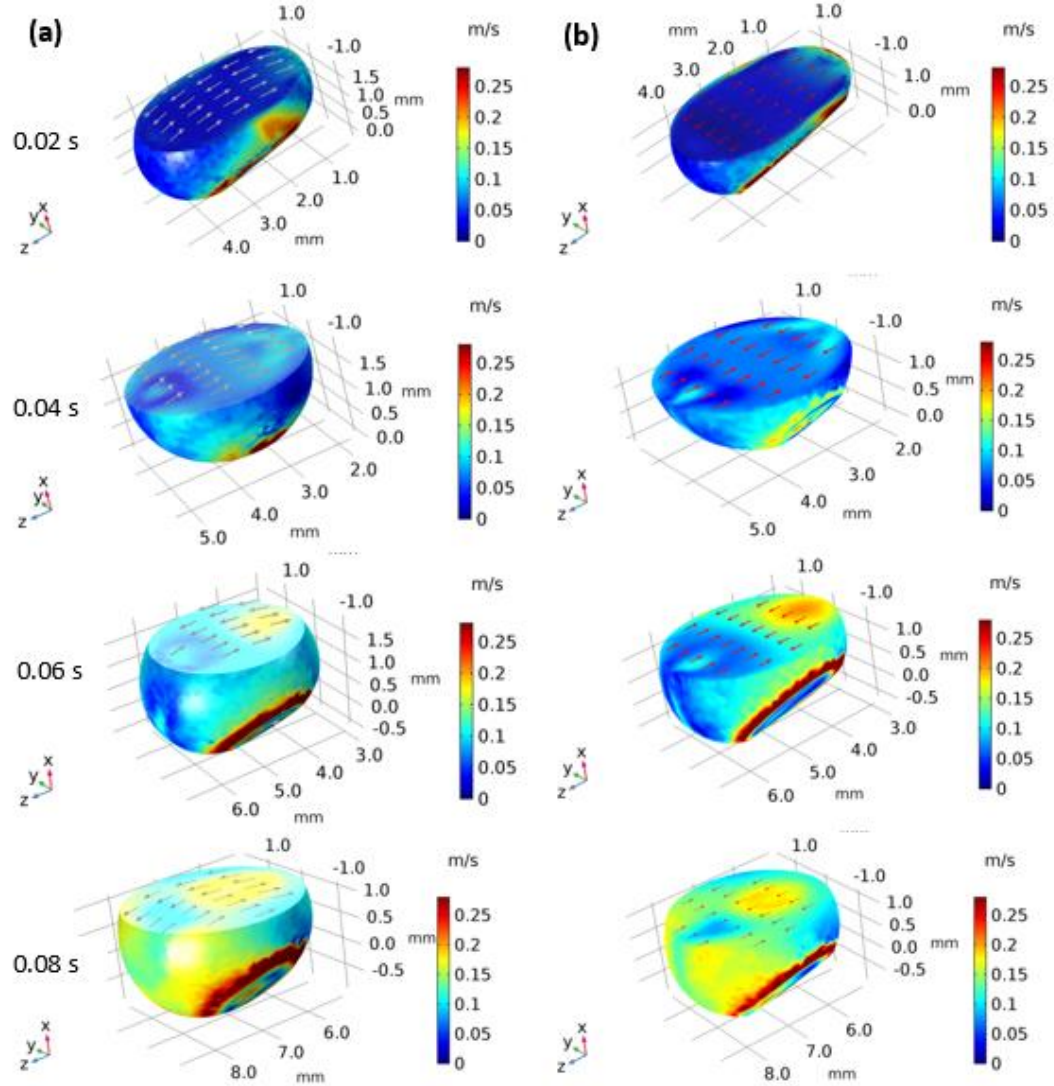


Figure-A10: Droplet spinning behavior down an inclined wedged hydrophobic channel for: (a) 145°-160° and (b) 150°-150° contact angles.

Variation of droplet contact area on wedged channels

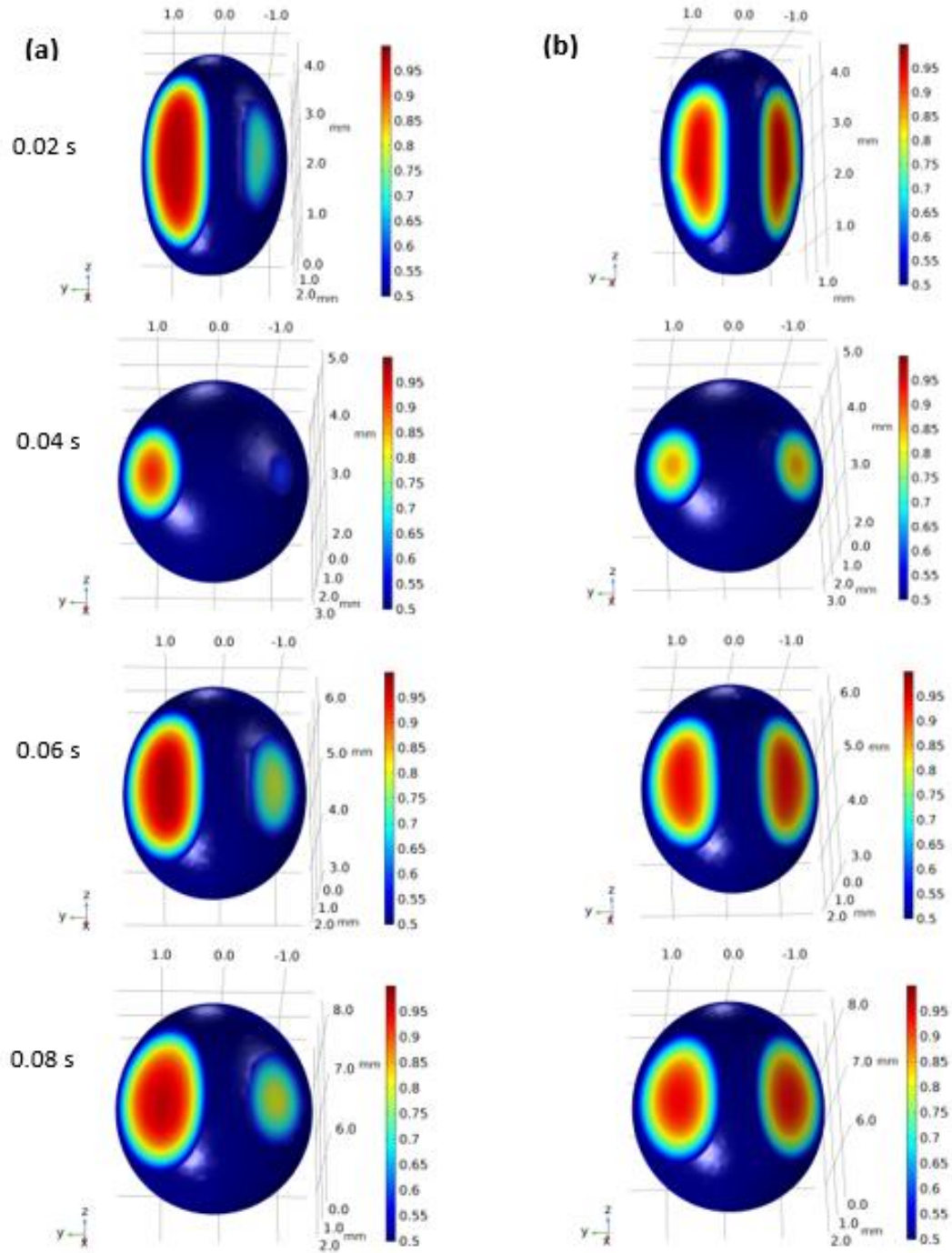


Figure-A11: Contact area during droplet rolling and spinning for: (a) 145°-160° and (b) 150°-150° contact angles

Variation of pressure across liquid droplet on wedge channels

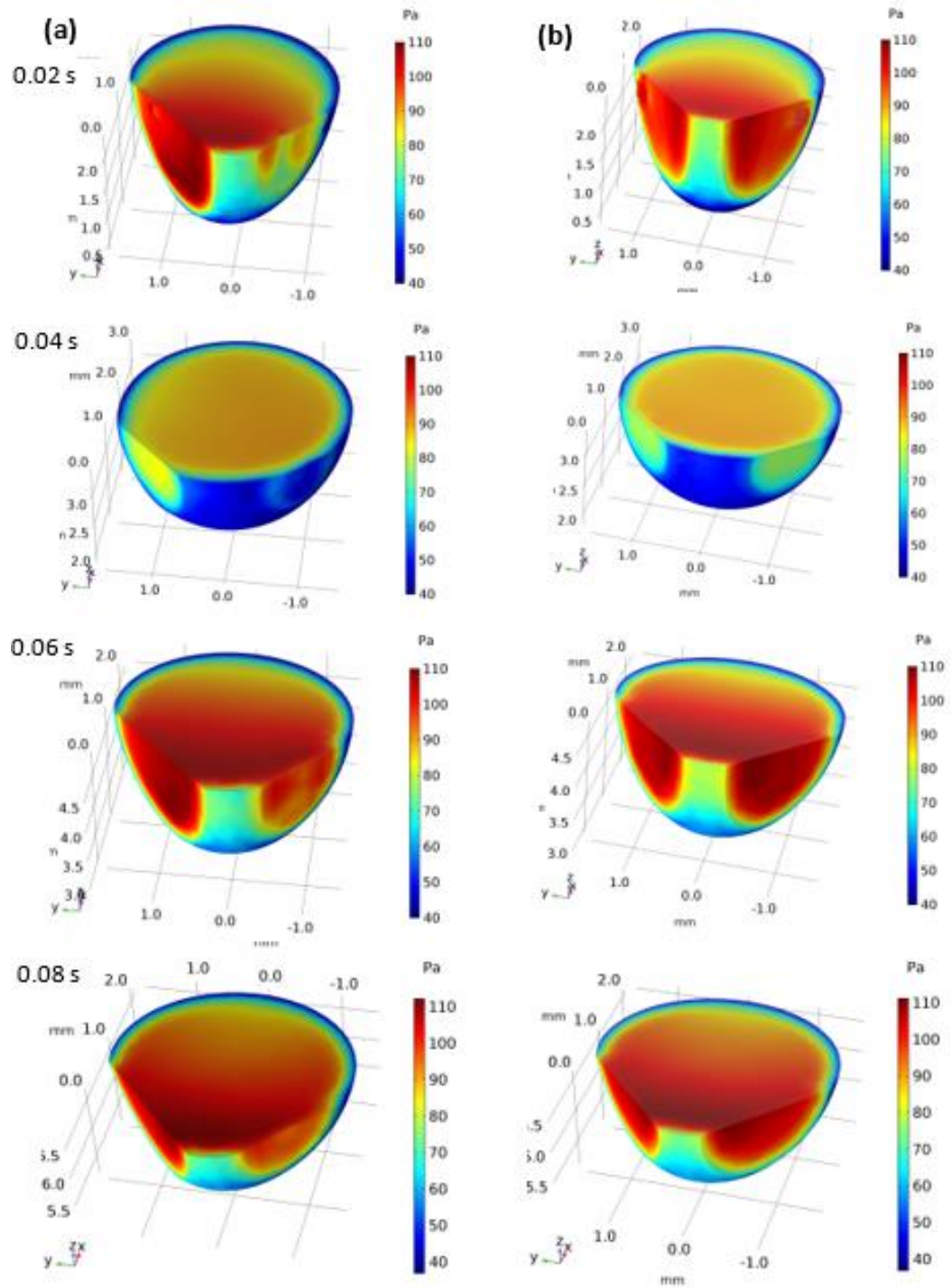


Figure-A12: Pressure during droplet rolling and spinning for: (a) 145°-160° and (b) 150°-150° contact angles

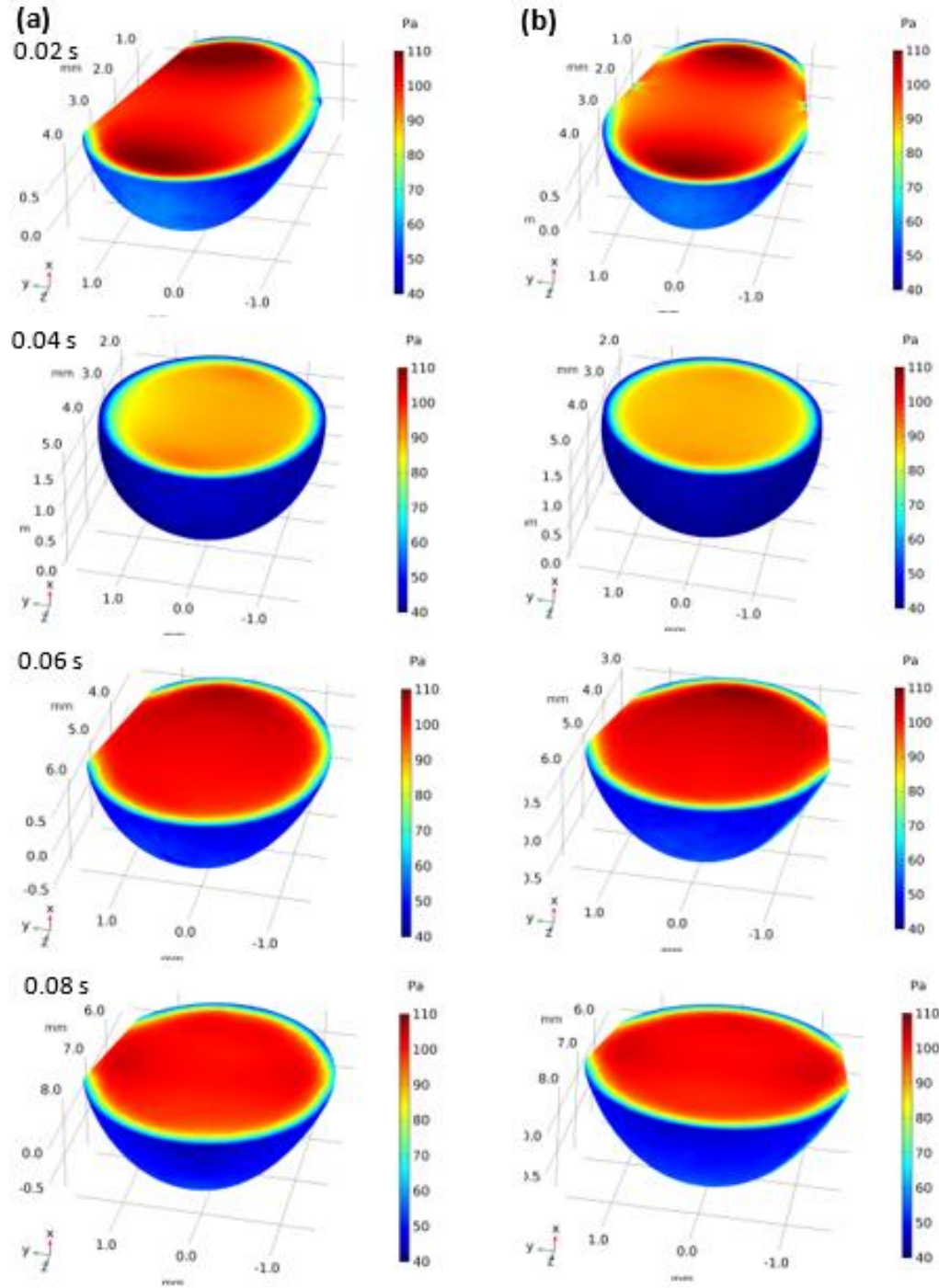


Figure-A13: Pressure during droplet rolling and spinning for: (a) 145°-160° and (b) 150°-160° contact angles

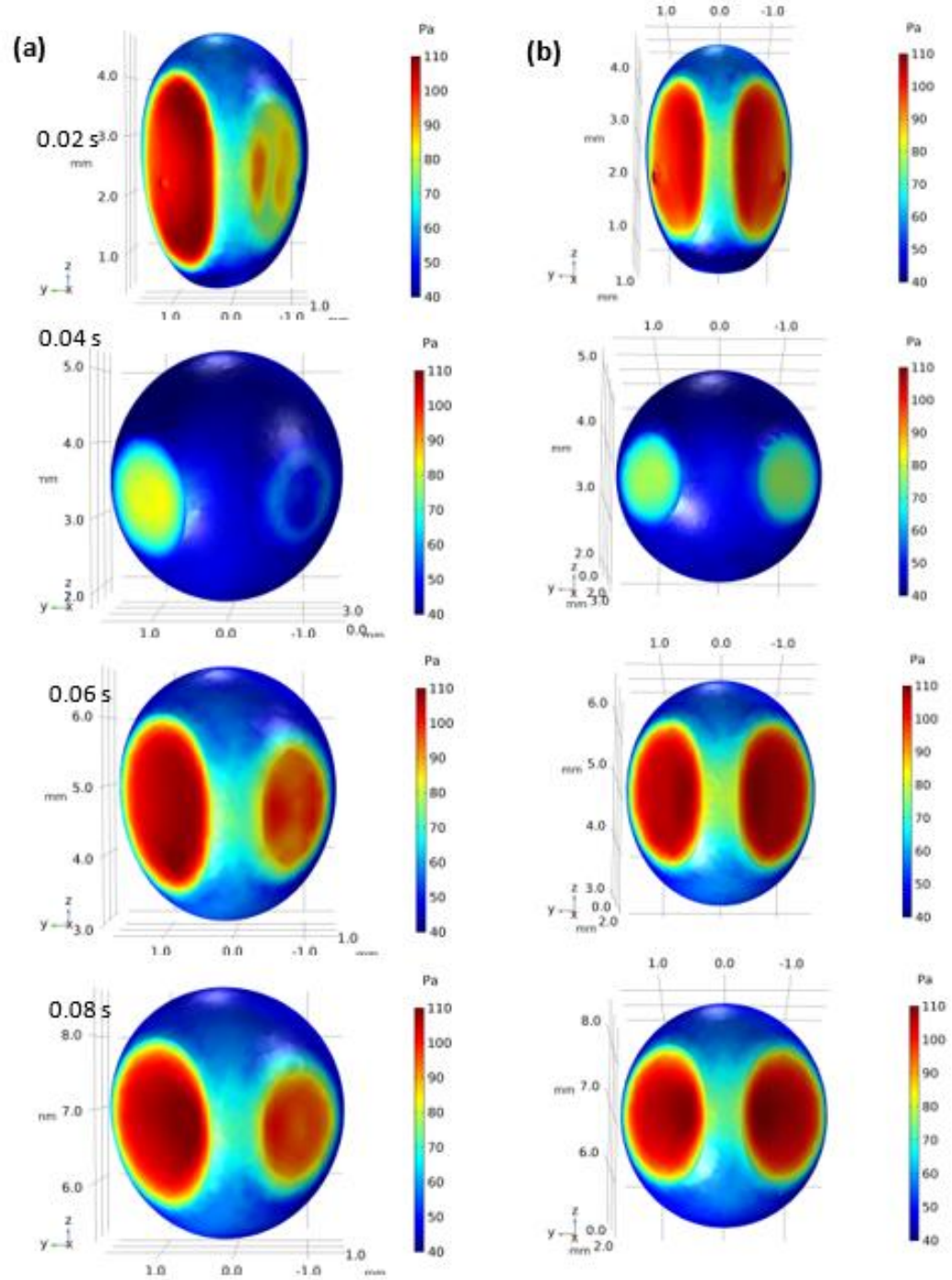


Figure-A14: Pressure developed at contact area during droplet rolling and spinning for: (a) 145°-160° and
(b) 150°-150° contact angles

Vitae

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