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Factors Affecting Surface Liquid Drop Ejection Downstream An Air Jet

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Abstract The purpose of this study is to investigate the effect of wettability between a surface liquid drop and the interacting surface on the ejection of the drop due to an air jet impinging. A newly measured parameter, the response time, was introduced to express the interaction effect through time. An experimental method was followed to get the wettability effect on the drop average velocity and response time. Pairs of inclination angles and offset ratios were discussed and three surface materials (Perspex, Glass and Nano-ceramic coated-glass) with different texture roughness were considered. Besides, three liquids were tested on Perspex. Observations using this experimental method and the fast-shooting camera technique showed that the ejection history is dependent on the wettability between the surface and the liquid. The velocity profiles of the liquid drop are found to be extremely different with different couples of liquids and surface materials. The wetting effect between the drop and surface is the dominant factor in the ejection process, that Perspex (the highest roughness) had an average drop velocity 3 times that of Glass (the lowest roughness), and the Nano-ceramic coated glass (the lowest wetting surface) had 40% increase in the drop velocity over Perspex. On the other side, the liquid properties are dominating the ejection process over the wetting effect.

Keywords Surface liquid drop, Air-liquid interaction, Drop ejection, Wettability, Impinging jet

1. Introduction

Momentum, heat or mass transfer across a wavy gas-liquid interface sheared by a turbulent gas stream are effective in many industrial processes that include gas absorption, evaporation and condensation. In addition, it often occurs in geophysical flows. The works of Radwan [1], and Salem et al. [2] stand as benchmarks in the research on liquid drop ejection by a gas stream. They extensively studied the surface interaction between water drops and air jet under combinations of jet to surface offset ratios (Z^*)– which is the quotient of the distance from nozzle mouth to the surface *h* by the nozzle outlet height *t*–and impinging jet inclination angle (φ) –which is the angle between the jet and the horizontal surface where the drop is set, Figure (1). They reported that a surface water drop subjected to plane air stream passes three physical regimes; namely, (1) a semi-stagnant regime encompassing small disturbance, (2) vortex and wave generation regimes, and (3) the start of dislodging (ejection regime). They claimed that the ejection regime may be classified into three separate sub-regimes, 1) trailing edge ejection, 2) leading edge ejection, and 3) fully ejected drop. They recorded the minimum jet speed required for drop ejection at the angle of inclination $\varphi = 30^{o}$ and offset ratio $Z^* = 2$.

The liquid properties, namely, density, viscosity and surface tension, greatly influence the behavior of a liquid drop sitting on a surface under the effect of a gas jet. The ejection process received attention for decades, since 1969. Woodmansee and Hanratty [3] studied the critical conditions and the mechanism of atomization for the co-current flow of air and liquid. High speed motion pictures revealed that atomization occurred by the removal of small wavelets (called roll waves) which exist on the top of flow surges in the liquid film. The critical conditions are characterized by two limiting behaviors. The critical condition for both thick and thin films is not strongly affected by changes in the fluid viscosity. From his calculations he concluded that the magnitude of the pressure variations caused by waves on top of the roll waves were large enough to account for their instability. Dussan [4] investigated the ability of a drop to stick to a solid surface when the surrounding fluid is in motion. He scaled the length, velocity and pressure for each case separately, introducing each group of scales into the momentum and the continuity equations to obtain the governing equation of the problem domain. He reported that the critical configuration was independent of the drop viscosity but two different drops would take different times to respond. Andong He and Belmonte [5] performed a theoretical and experimental study on the deformation of a free surface between two fluids in a gravitational field due to a jet in the low-density fluid impinging at right angles to the surface. They found that surface tension, fluid viscosity and the container size have negligible effects on the cavity; it is rather the density ratio that plays a role in determining the cavity size. This paper is divided into four sections; Surface wettability effect, Experimental set-up including flow visualization techniques, measurements techniques, preliminary test procedure and experimental procedure, Results and discussion, and finally, Conclusion.

Surface Wettability Effect

A drop of liquid sitting on a plane horizontal surface will be held in place by surface tension. But when a liquid is ejected by a gas jet on a horizontal solid surface, the motion depends on the wettability of the liquid to solid. Wettability can be defined as the propensity of liquid to spread over a solid surface, it is the property relating the surface to the liquid. Wettability studies usually involve the measurement of contact angles (θ) – which is the angle between the surface and the tangent to the drop surface – as the primary data, which indicates the degree of wetting when a solid and liquid interact. Small contact angles ($\ll 90°$) correspond to high wettability, while large contact angles ($\gg 90°$) correspond to low wettability. The liquid deposited on the solid surface, under gravity has tendency to spread until the cohesion (internal forces) of liquid, the gravity forces and capillary (surface tension) forces are in balance. Surface roughness affects the movement of an object on a surface and decreases the kinetic energy of the motion. But when a liquid is ejected by a gas jet on a horizontal solid surface, the resulting motion, however, depends on the compound effect of both the liquid properties and surface roughness of the interacting surface under investigation. The topic of wetting has received tremendous interest from both fundamental and applied points of view. It plays an important role in many industrial processes, such as oil recovery, lubrication, liquid coating, printing, and spray quenching [6]. In recent years, there has been an increasing interest in the study of super-hydrophobic surfaces, due to their potential applications in different fields for example, self-cleaning, Nano-fluidics, and electro-wetting. However the wettability of surfaces can be strongly affected by surface roughness. This influence can be very significant for static and dynamic wetting [7]. To conclude, the wettability affects the hydrodynamics of liquid motion on solid surfaces. However, the effect of both surface and liquid properties on the ejection history of a liquid drop downstream a gas flow is not well-covered in the previous studies reviewed. The objective of this present study is to investigate experimentally, the effect of fluid properties and surface roughness on the ejection performance of a liquid drop set on a horizontal solid surface under the effect of a plane air jet. The response of a drop to plane air jet is thought to be sensitive to fluid density, viscosity and surface tension as well as the surface texture.

Experimental set-up

The present facility used by Radwan [1] and Salem et al [2]; was developed and made available to simulate the real situation in industrial applications. The set-up is mainly a two-dimensional plane offset jet impinging on a horizontal flat plate at different angles of inclination. The mechanism allows controlling a package of primary independent geometrical variables such as the inclination angle (φ), offset ratio (Z^*) and the nozzle aspect ratio ($B^* = b/t$), where b is the nozzle span, and t is the nozzle outlet height (3.8 mm). Such facility produces a variety of flow field configurations, each of which has more than one physical regime. More specifically, this type of impinging flow is characterized by a longitudinal variation of curvature, skewed impingement on to the flat plate, a recirculation region, and a development of a wall jet region, Figure (1).

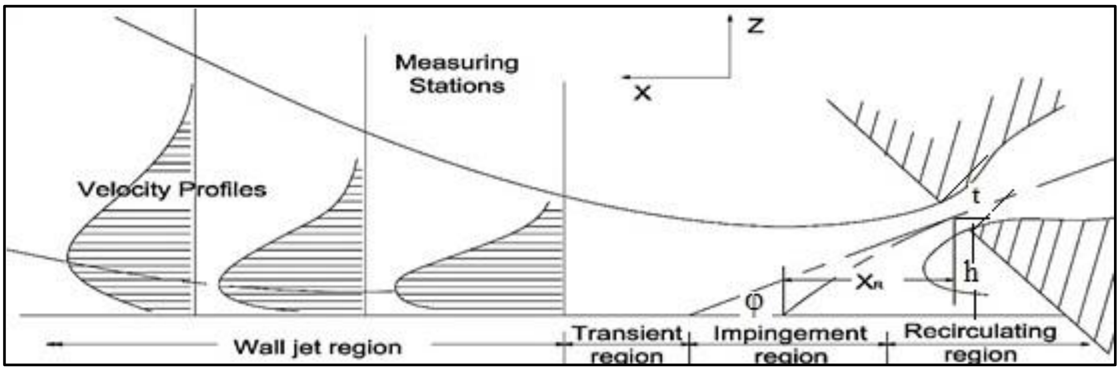
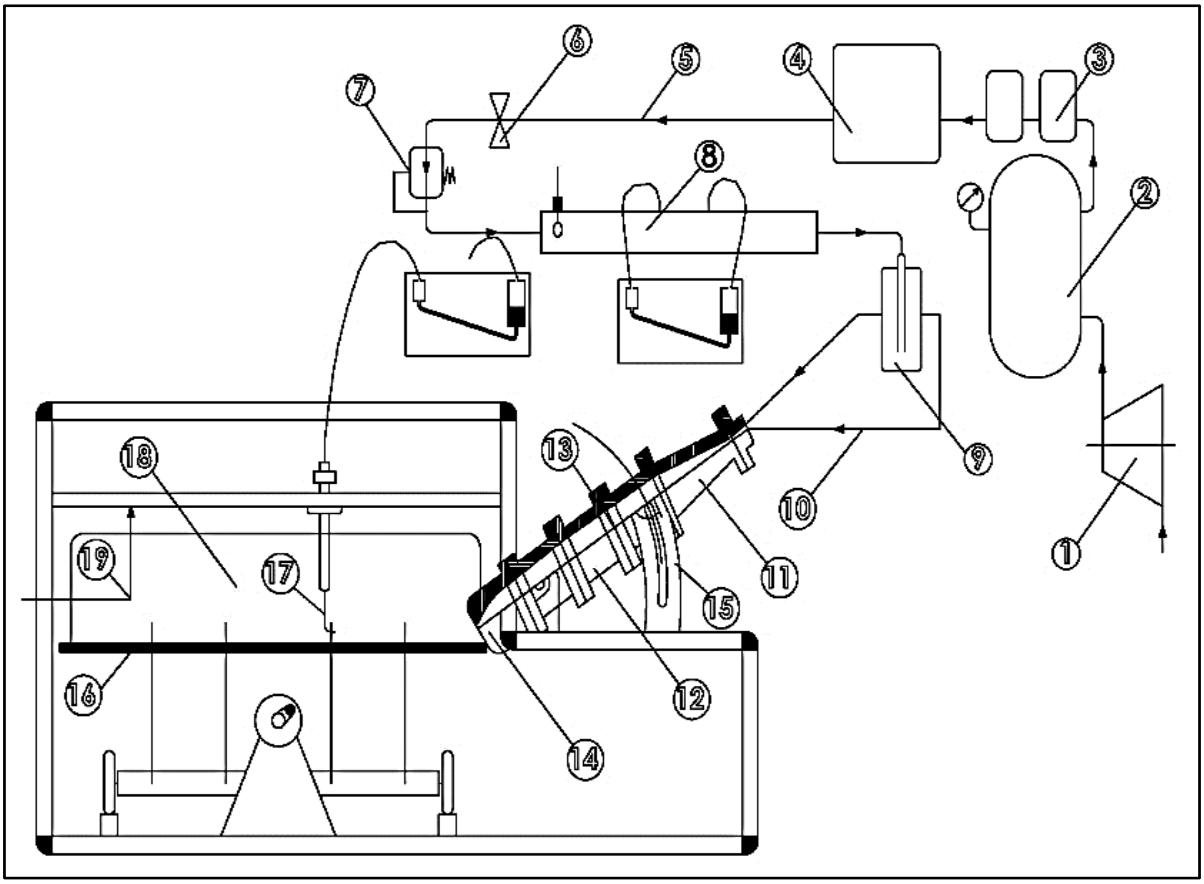


Figure 1: Physical regimes associated with impingement plane jet

Figure (2) illustrates a schematic drawing of the experimental set-up facility. It consists of:

1. Head station for compressed air: Ingersoll-Rand 63 kW-three phase screw-type compressor delivering 8.5 cubic meters free air per minute, a cubic meters capacity storage tank (Max. pressure is 8 to 10 bar), air filters, mass refrigeration dryer unit, one inch stainless steel ball valve (Main supply valve).
2. A looped hose, pressure regulator (Commozi-Co) with regulation range from 0 to 12 bar, orifice meter arrangement, seven-outlet distributor.
3. Jet generation wind tunnel.
4. Pressure regulator (Metal work) with regulating range of (0-12 bar).



1: Screw compressor, 2: Pressure tank, 3: Air filter, 4: Mass refrigeration air dryer,
5: Main supply pipe, 6: Main supply valve, 7: Pressure regulator, 8: Orifice meter arrangement,
9: Seven-Outlet distributer, 10: Flexible hoses, 11: Wide angle diffuser, 12: Plenum chambers, 13: Screens,
14: Elliptic contoured nozzle, 15: Adjustment mechanism of inclination angle, 16: Impingement plate,
17: Pitot-tube attached to an inclined manometer, 18: Side walls, 19: Exhaust of the spent air

Figure 2: Schematic diagram of the apparatus used (not to scale)

Flow Visualization techniques

The drops were visualized using either spherical glass micro balloons (50 – 75 micrometer) or Potassium Permanganate (Dye) and a Nikon, D3400 (video/still) Camera (24.2 mega pixels – 18X optical zoom and 1/4000 shutter speed with 60 frames per second) was used to record plan view videos and still side view snapshots.

Measurement techniques

1. Surface tension coefficient and contact angle

Numerous methods have been developed to determine the liquid surface tension and contact angle from the shape of a sessile drop, pendant drop, or captive bubble. Ideally, the shape of a liquid drop set on a solid surface depends on the combined effects of interfacial and gravitational forces. Surface tension tends to minimize the surface area by making the drop spherical, while gravity deforms the drop in two ways: (1) by elongating a pendant drop and/or (2) flattening a sessile drop. The so named θ/2 method is widely used to analyze the profile of a sessile drop. In this analysis, the liquid drop is assumed to be part of a sphere. Geometrically, the contact angle can be calculated by measuring the drop diameter, 2d and the height of the apex, h, Figure 3.

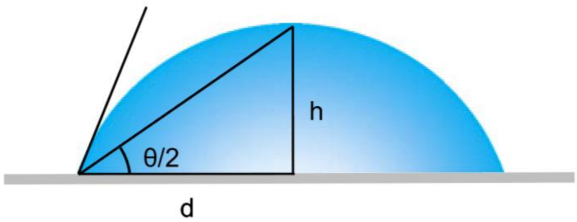


Figure 3: Illustration of the drop contact angle

$$\frac{\theta}{2} = \tan^{-1}(\frac{h}{d}) \tag{1}$$

This method yields reasonable results when the liquid drop is extremely small. However, the spherical shape assumption cannot be applied if the drop shape is large enough to be affected by gravity. Wang et al [8] presented a physically-based method to enforce contact angles at the intersection of fluid free surfaces and solid objects, allowing us to simulate a variety of small-scale fluid phenomena including water drops on surfaces. The heart of this technique was a virtual surface method, which modifies the level set distance field representing the fluid surface in order to maintain an appropriate contact angle. The surface tension that is calculated on the contact line between the solid surface and liquid surface can then capture all interfacial tensions, including liquid-solid, liquid-air and solid-air tensions.

2. Air velocity

A stainless-steel Pitot-tube, calibration coefficient 0.96 with outer diameter = 1.25 mm, inner diameter = 0.9 mm (length = 25 times the outer diameter) was used to measure the jet velocity at the nozzle outlet and an inclined U-tube manometer filled with water was used to measure the pressure drop across the orifice meter-arrangement.

3. Drop size

A digital caliper and micrometer with simple DC electric circuit was utilized to measure the thickness of drop. Finally, a 3-cm^{3}medical syringe was used to produce the drop.

4. Drop velocity measurements

The screenshots of the fixed video recordings were used to measure the drop velocity by cutting the videos using Movie Maker™, calculating the time required for the drop to cut fixed distances and then estimating the drop average velocity. When analyzing the drop velocity curves it was found that the maximum velocity, U_{max} during the ejection history is located in the first interval of measurement.

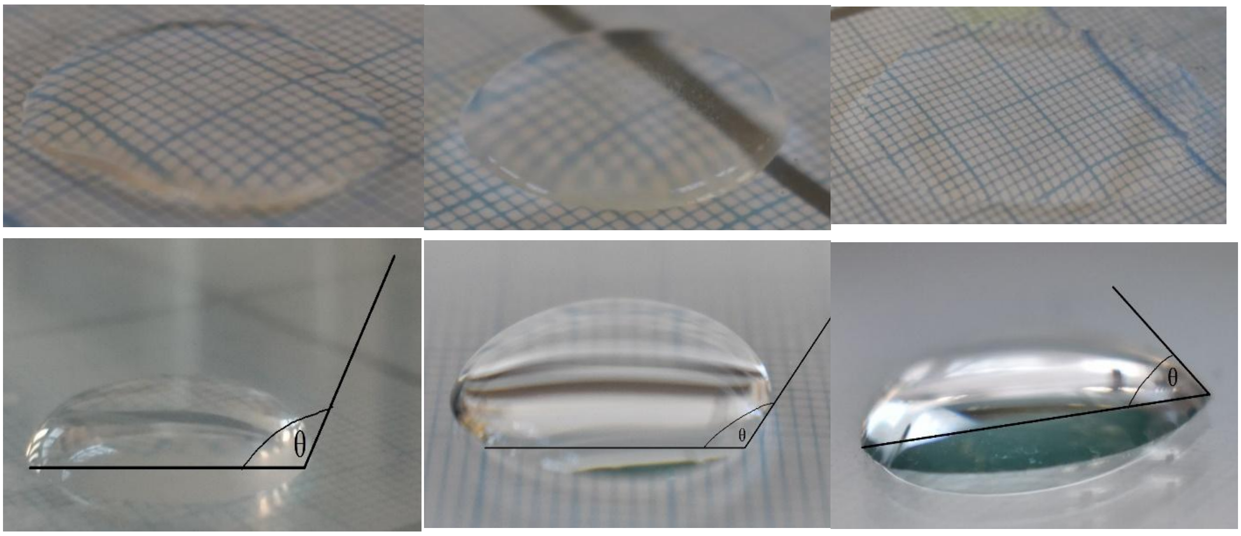
5. Surface roughness

Three different surface materials were used to illustrate the effect of surface roughness on the ejection process. These are, namely, Perspex, glass and Nano-ceramic coated glass. The surface roughness of every one of these materials was measured by a 'Surtronic-2' roughness meter. The roughness was measured four times at sparse spots on each surface. The final average values are listed below in Table (1).

Table 1: Surface roughness values for the considered materials

Case	**Roughness value, µm**
Perspex	0.090
Glass	0.018
Nano-ceramic coated glass	0.022

Figure (4) illustrates water drops are wetting different solid surfaces. The contact angle is less than 90^o with Glass, larger than 90^{o}withPerspex and Nano-ceramic coated glass ordered from the smallest to the largest.



Perspex **Nano-ceramic** **Glass**

Figure 4: Two different views for a water drop on the tested surfaces, on the top is an inclined photograph and the upper is the elevation photograph

6. Fluid properties

Three liquids were examined in this study, namely, water and two grades of oil. The liquid density was measured by a JYL 50 milliliter-capacity Pycnometer. Meanwhile, dynamic viscosity in centipoise was measured at 25^{o}c by a Brook Field Viscometer. Finally, the fluid surface tension was estimated using capillary tube theory employing the relation

$$\sigma = \frac{2}{\rho \; g \; r \; \left(l + \frac{1}{3r} \right)} \quad (2)$$

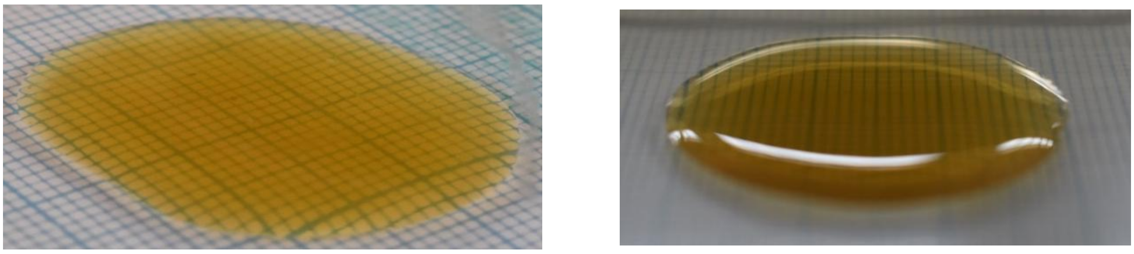
Where σ is the surface tension of the liquid(N/m), ρ is the liquid density (kg/m^3), r is the tube radius (m), $g$is the gravitational acceleration (9.81 m/sec^2) and l is the liquid height (m) in the capillary tube.The tube radius was 1mm. The properties of the tested fluid are summarized in Table (2).

Table 2: Properties of the tested liquids

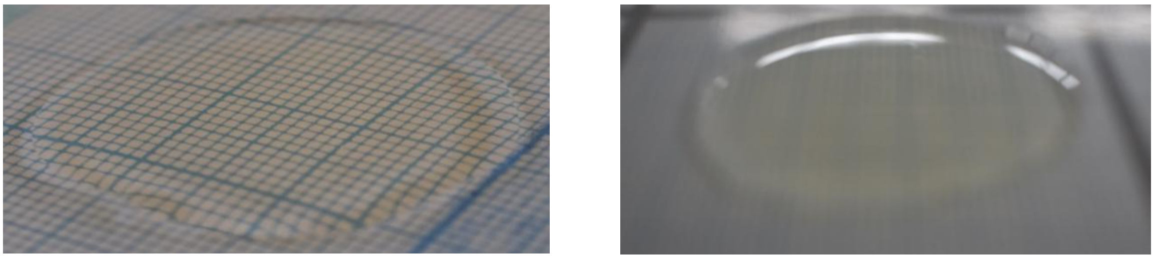
	Surface tension (N/m)	**Density(g/ml)**	**Dynamic Viscosity(cP)**
Water	0.072	1	1
Oil-1	0.078	0.92	58.2
Oil-2	0.081	0.884	177.6

Preliminary Test Procedure

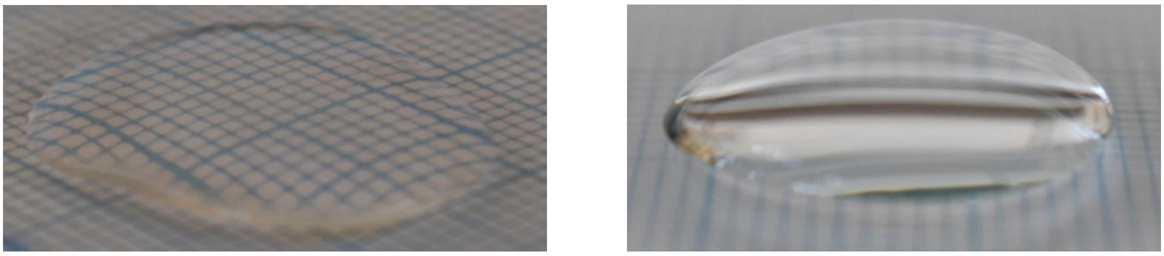
Three liquid drops on the Perspex surface were subjected to air streams under the same conditions (offset ratio =2, the inclination angle =30^o, R_{ej} = 25.5 *10^3), where R_{ej} is the jet Reynolds number. The oil drops could not withstand a height more than 0.86 mms although the water drop withstood up to 3 mms. Figure (5) shows two views for the three tested liquid drops on the Perspex surface.



Oil-2



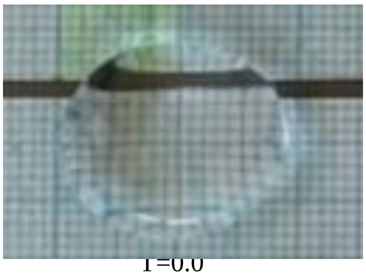
Oil-1



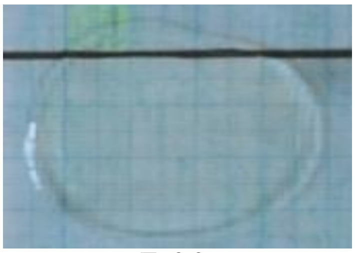
Water

Figure 5: Two views for liquids, on the left is inclined 30 degree from the horizontal photograph and on the right is a sided-view photograph

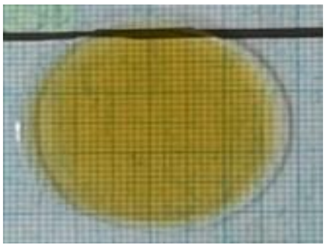
The wettability of oils and water to the perspex surface is completely different that the oil drop is flattened to about 35mm diameter while it is 17 mm in the case of water for the same volume in the steady state. The overall ejection profile is completely different for oils and water as shown in Figure (6). For water –low surface tension, low viscosity and low wettability – the drop takes less time to respond. The drop average velocity is higher than that of oils, the drops cut the same distance faster and the drop is moved as one unit, on the other side, the oil drops –high surface tension, high viscosity and good wettability – the drops respond very slowly with very small average velocity and the connecting liquid spreads out with extremely reduced thickness.



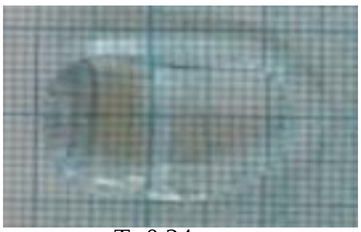
T=0.0



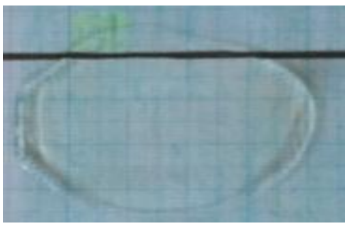
T=0.0



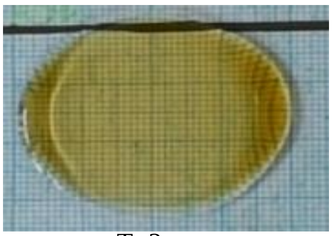
T=0.0



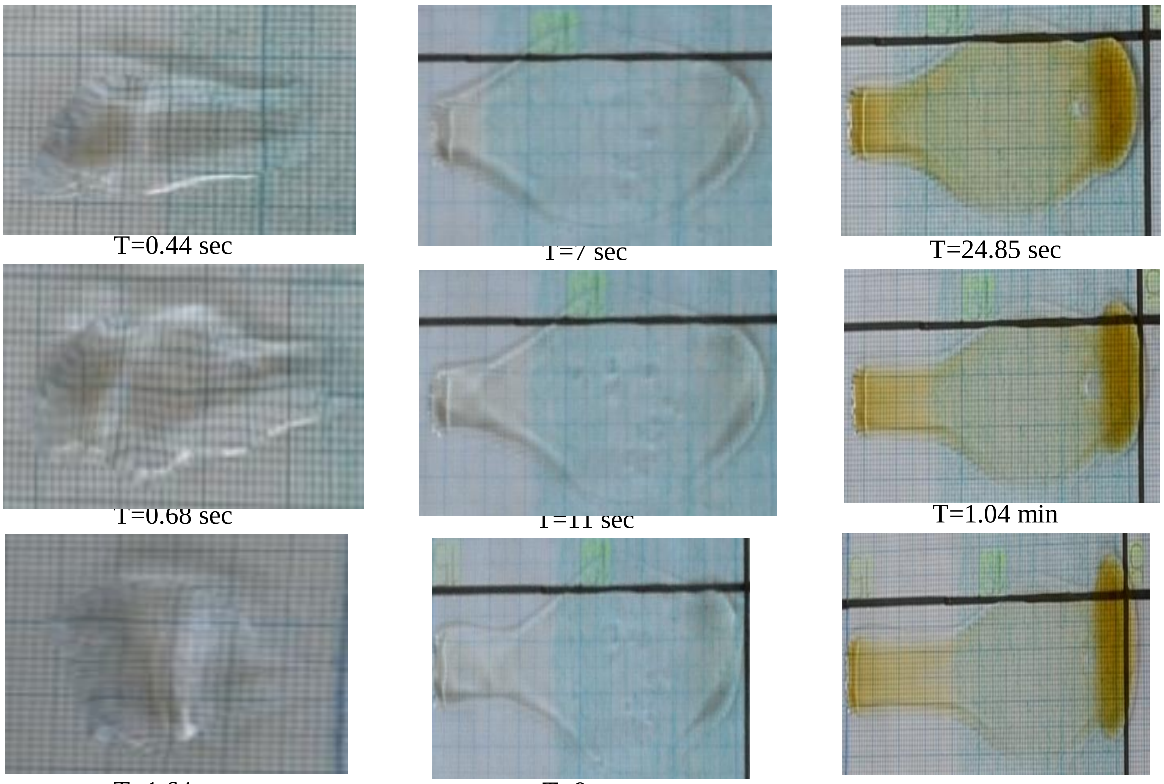
T=0.24 sec



T=2.93 sec



T=3 sec



T=0.44 sec T=7 sec T=24.85 sec

T=0.68 sec T=11 sec T=1.04 min

T=1.64 sec T=9 sec T=1.50 min

(a) Water Drop **(b) Oil-1 Drop** **(b) Oil-2 Drop**

*Figure 6: Ejection history of water and oil drops, the ejection history is going from up to down and the air jet is directed from left to right and all are for the case 15-degree inclination and 12.63 offset ratio, time is counted starting from the effect beginning, t=0.0, for a R_n=25.5*10^3*

Experimental Procedure

In order to establish the different physical regimes associated with the interaction between a plane air jet and surface liquid drop, the following experimental procedure was followed:

1- Adjustment of geometrical parameters to the required settings, these parameters were:
   a. The inclination angle φ.
   b. The offset ratio Z*.
   c. The drop supporting surface horizontality.
2- Measurements of the following ambient conditions which mainly were:
   a. Atmospheric pressure.
   b. Atmospheric temperature.
   c. Relative humidity.
3- Injection of a proper amount of liquid using a medical syringe at the critical distance X_{cr}. The critical distance X_{cr} is the distance measured from the surface edge at the nozzle outlet till the position at which the drop is critical to be ejected inwards or redirected by the recirculating effects, Figure (1).The injected volume of liquid is selected to justify that the drop diameter is 17mm;this gives a Bond Number B_o= 8.5 [1],

$$Bo = \frac{(\rho_L \ - \rho_g) \, g \, V^{*2/3}}{\sigma} \tag{3}$$

   Where $V^*$is the volume of the surface drop (m^3),$\rho_L$is the liquid density and $\rho_g$is the gas density.
4- Starting the air flow at a fixed setting of the pressure regulator which provides the highest flow rate. The working jet Reynolds number is obtained for this setting and its value was determined as 25.5*10^3.
5- Obtaining the critical distance.
6- Video recording the ejection process using the plan view capturing fixed video camera.

7- Analyzing the data to calculate the average drop velocity.
8- Estimating the response time of the liquid drop T_r which is the difference between the time of starting the movement T_{mov} and the time of starting the effect of the interaction T_{int},
Where the T_{int} is the time that the crescent shape appears on the edge exposed to the jet [1] and the T_{mov} is the time in which the drop is just about to be ejected.

$$T_r = T_{mov} - T_{int} \quad (4)$$

9- Re-adjusting the inclination angle and measuring the corresponding offset ratio.
10- Analyzing the data.
11- Repeating for another surface/liquid.

The present measurements and observations were obtained for inclination angles φ = 0, 15, 30 and 45 degrees, and offset ratios Z^* =4.5 and 12.63. These combinations of inclination angles and offset ratios ensured that the drop was always subjected to fully developed jet velocity profile. Water drop height was nominally 2.36mm, and 0.86mm for the oil drops. A ±0.01mm is the maximum estimated error of this drop height.

Results and Discussion

The results of the average velocity, critical distance and response time at different inclination angles and offset ratios are illustrated and discussed in this section. In the following demonstrations, water was used as a reference liquid to compare the ejection characteristics of the different surface materials and perspex was used as a reference surface to compare the different liquids and the air jet Reynolds number = $25.5*10^3$, this results in a 0.4553 m/s jet velocity at the nozzle exit.

Critical distance

Figures (7) and (8) illustrate the effect of surface material and liquid properties on the critical distance. It is noticed that the critical distance is almost unaltered by either.

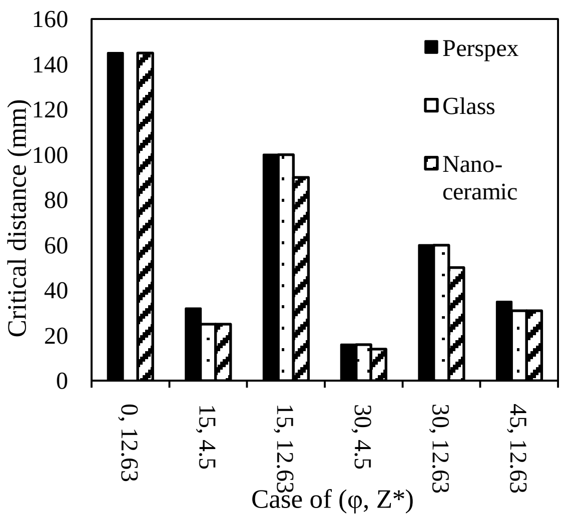


Figure 7: Critical distance versus surface materials. Water drop, R_n =25.5*10^3*

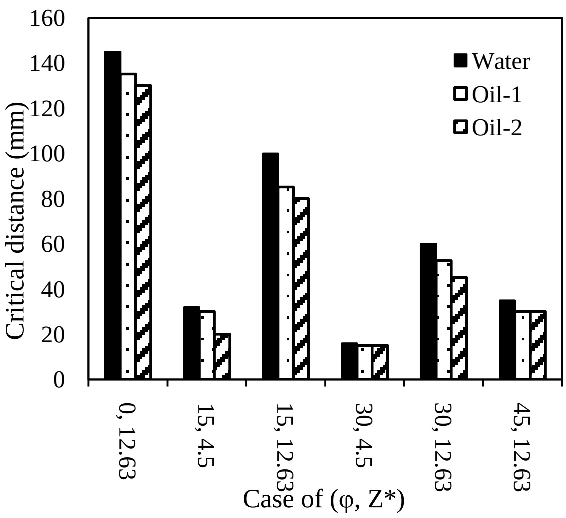


*Figure 8: Critical distance versus liquid properties. Perspex surface, R_n =25.5*10^3*

** Glass has no critical distance in (0, 12.63) case because the air jet is weak to eject the drops that is staked on the surface, the drops are still stagnant along the experiment time i.e. the drag forces (due to the pressure drop across the drop) is less than the sum of the capillary forces inside drop (due to surface tension) and the sticking effect so; the drop remains stable.*

From Figure (7), the critical distance is nearly the same although Nano-ceramic case gives less critical distances. The lower the offset ratio the lower the critical distance e.g. Perspex; the 30- degree inclination with 4.5 offset ratio has 16 mm critical distance while the 12.63 case has a critical on 60mm, that is happened because the jet effect is stronger when the offset ratio is small, so the critical distance is reduced. On the other side; for the same offset ratio; the lower the inclination angle the higher the critical distance e.g. for 12.63 offset ratio cases; 45° has a 35 mm critical which is less than 60 mm ‘30° case’, 100 mm ‘15° case’ or 145 mm ‘0° case in perspex’, this is due to higher impinging effect for the air jet, Figure(1).

Figure (8) shows that the critical distance is slightly different based on the density ratio between the two fluids [5] that the air could eject smaller density liquids at earlier distances of the impinging period; that X_{cr} for water > X_{cr} oil-2 > X_{cr} oil-1, also for the same inclination angle the lower the offset ratio the lower the critical distance i.e. for 30- degree inclination cases 4.5 offset ratio has 16 mm critical distance while the 12.63 case has a critical distance of 60 mm, on the other side, for the same offset ratio; the lower the inclination the lower the higher the critical distance i.e. for 12.63 offset ratio cases 45° has a 35 mm critical which is less than 60 mm ‘30° case’, 100 mm ‘15° case’ or 145 mm ‘0° case’ in water as depicted before in the previous paragraph.

Response time

The response time is significantly affected by the surface material (Fig.9) and liquid properties (Fig. 10). There is apparently depicted that as the jet becomes further apart from the drop, i.e. the offset ratio increases, it becomes less effective on the drop and the response time extends. By contrast, the increase of the inclination angle causes the response time to shorten. This may be because as the inclination angle increases, the critical distance decreases i.e. the drop becomes closer to the nozzle and hence the ejection is carried out by a higher-velocity section in the jet. The zero inclination, however, results in a relatively short response time, most possibly because the drop is closely and directly subjected to the jet. In addition, as the wettability intensifies by either roughness increase or surface tension increase, the response time increases. It is notable that water drop resistance dramatically falls after 15-degree inclination angle. This is true no matter the surface roughness is.

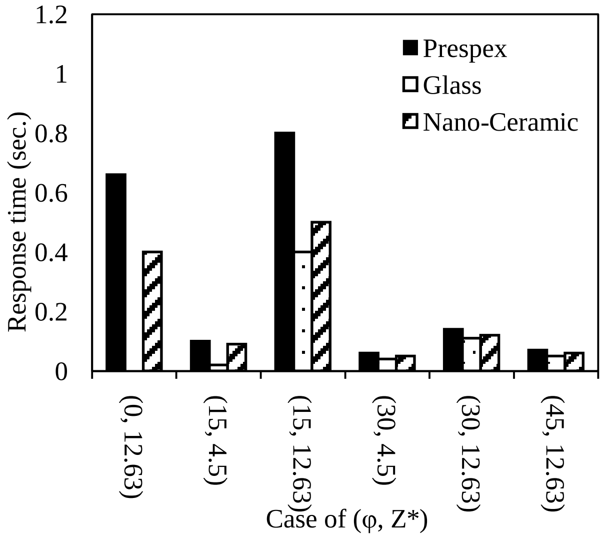


Figure 9: Response time versus surface material, Water drop, R_n =25.5*10^3*

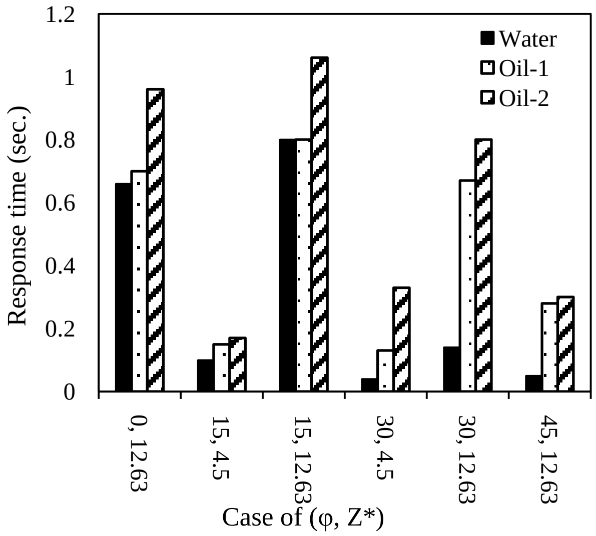


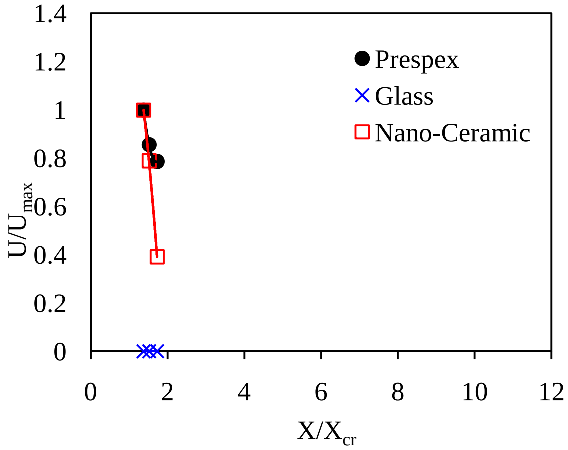
*Figure 10: Response time versus Liquids, Perspex surface, R_n =25.5*10^3*

* Glass has no critical distance in (0, 12.63) case, the reason was previously mentioned above.

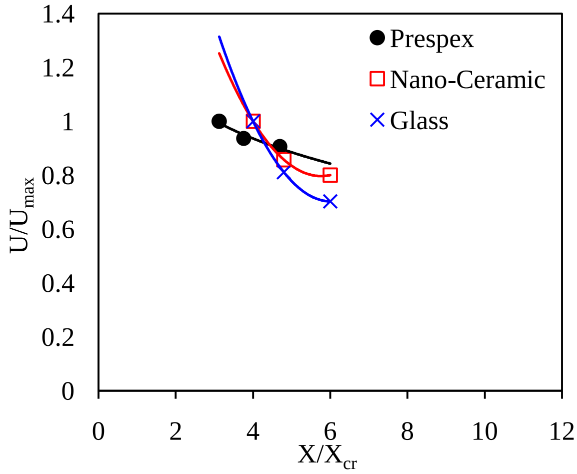
Drop velocity

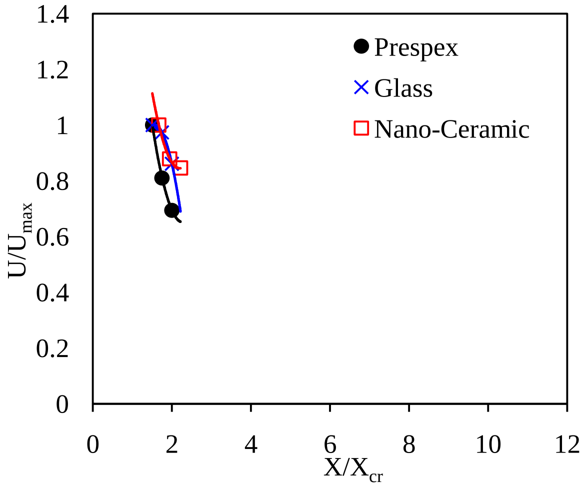
For the same liquid, Figure (11), or the same surface material, Figure (12), at constant inclination angle, with low offset ratios, e.g. (b) and (c) or (d) and (e), high velocities are noticed and this is apparently because the ejection jet stream is closer to the surface than the case of high offset ratios. Also, at constant offset ratio, (b) and (d) or (a), (c), (e) and (f), high velocities in cases of high inclinations are resulted. This is believed to be due to the fact that the intensive impingement effect is higher in large inclinations.

Overlooking, Figure (11), at the same condition of offset ratio and inclination angle, the ejection velocity is higher in case of nano-ceramic coated glass than perspex case when compared with glass. This is attributed related to the nature of wettability of water to glass, so the motion is slow due to stacking effects. This is expected since the roughness of the perspex is lower than that of nano-ceramic. This was cited but not experimentally approved in [7]. On the other side, Figure (12), at the same conditions of offset ratio and inclination angle, it was predicted that oil drops will respond in a longer time and the velocities will be very low compared to water drops.

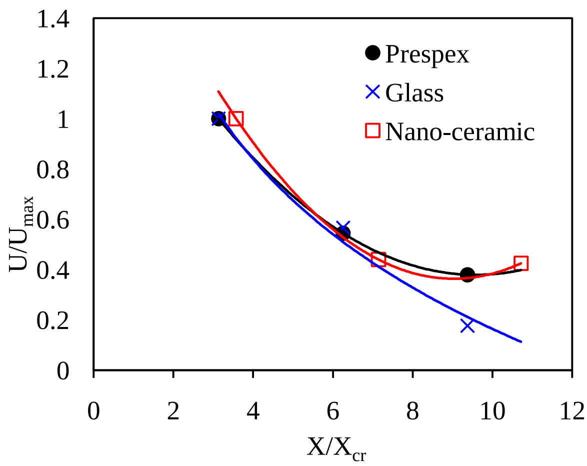


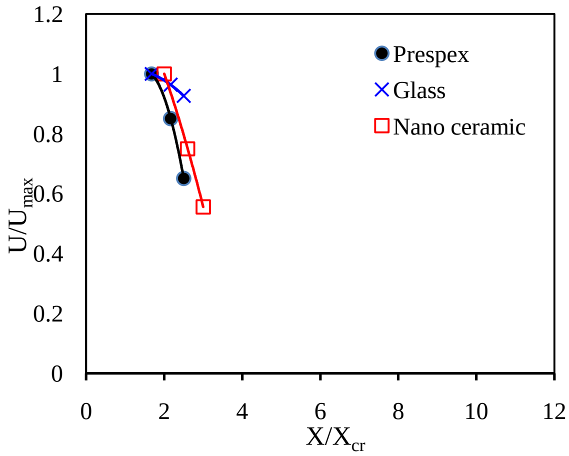
(a) 0^o inclination, 12.63 offset ratio*



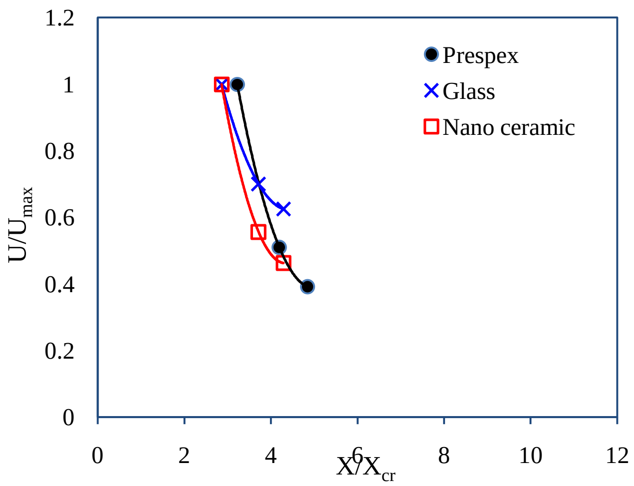


(b) 15^o inclination, 4.5 offset ratio (c) 15^o inclination, 12.63 offset ratio





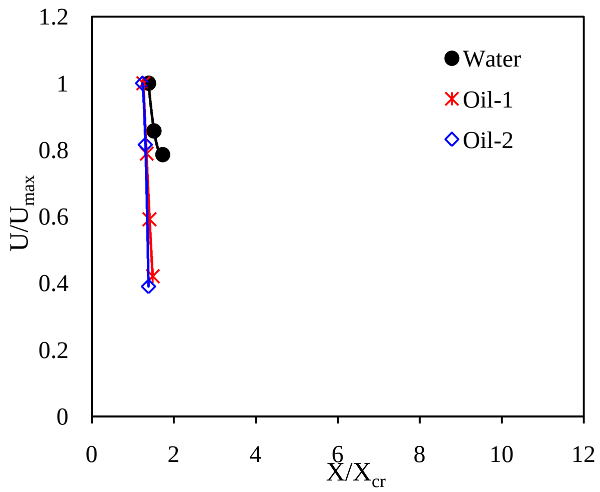
(d) 30^o inclination, 4.5 offset ratio **(e) 30^o inclination, 12.63 offset ratio**



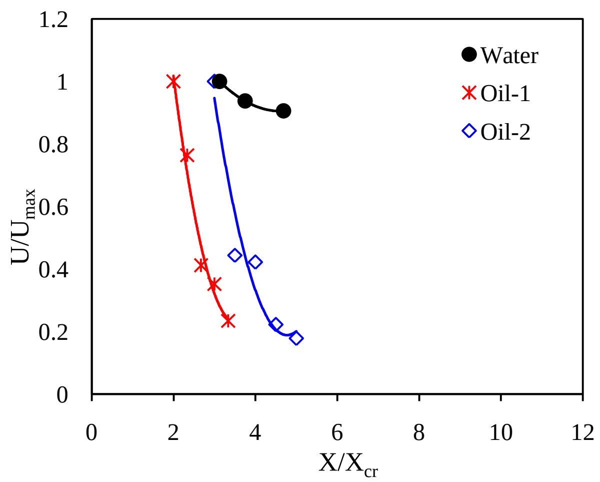
(f) 45° inclination, 12.63 offset ratio

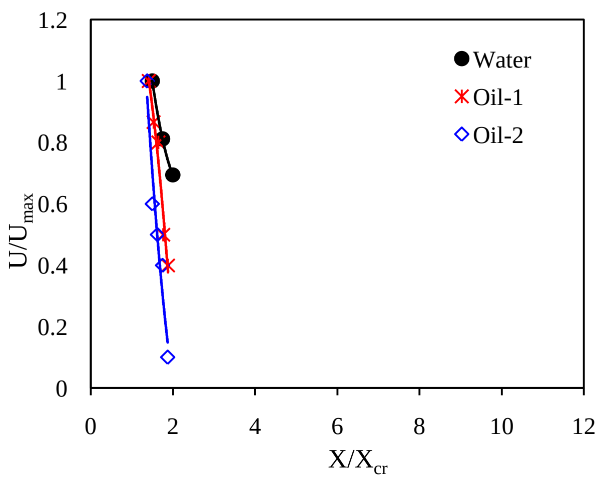
*Figure 11: Effect of surface roughness on the average drop velocity. The lines are 2nd degree polynomial-fittings, water drop and R_n =25.5*10^3*

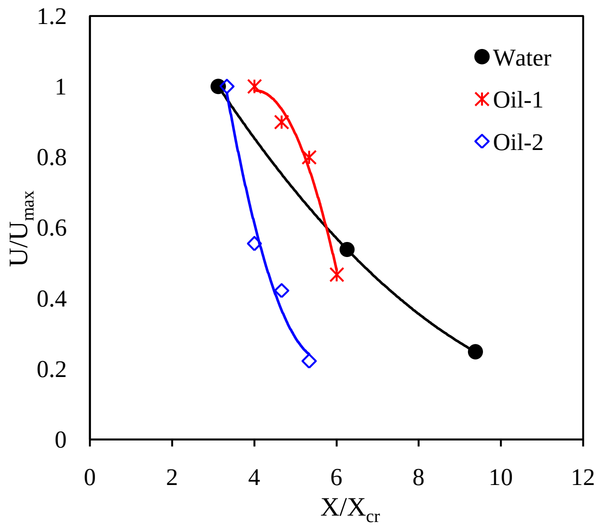
* Glass has no critical distance in (0, 12.63) case, the reason was previously mentioned above.



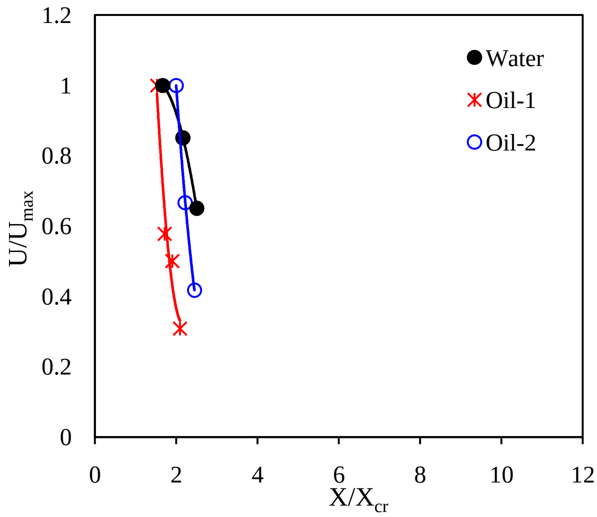
(a) 0° inclination 12.63 offset ratio



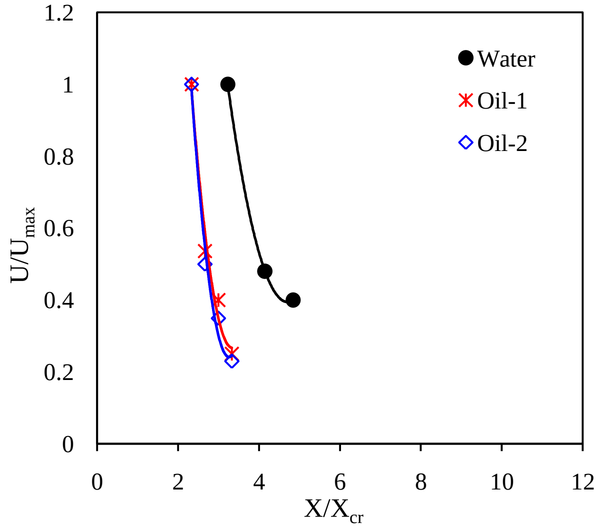




(d) 30° inclination 4.5 offset ratio



(e) 30° inclination 12.63 offset ratio



(f) 45° inclination 12.63 offset ratio

*Figure 12: Effect of liquid properties on the average drop velocity. The lines are 2nd degree polynomial-fittings, perspex surface and R_n =25.5*10^3*

Maximum ejection velocity

Where weber number W_b based on U_{max} ,W_b= $\frac{\rho U_{max}^2 V^{*1/3}}{\sigma}$ and U_{max} is the maximum drop velocity measured during the experiments.

It is obviously that, Figure (13), that the W_b is larger for nano-ceramic than the other surface materials as shown above in Figure (11). Also water results in much larger W_b than other liquids because it has the least surface tension, the denominator, and the least dynamic viscosity e.g. the highest velocities, Figure (14).

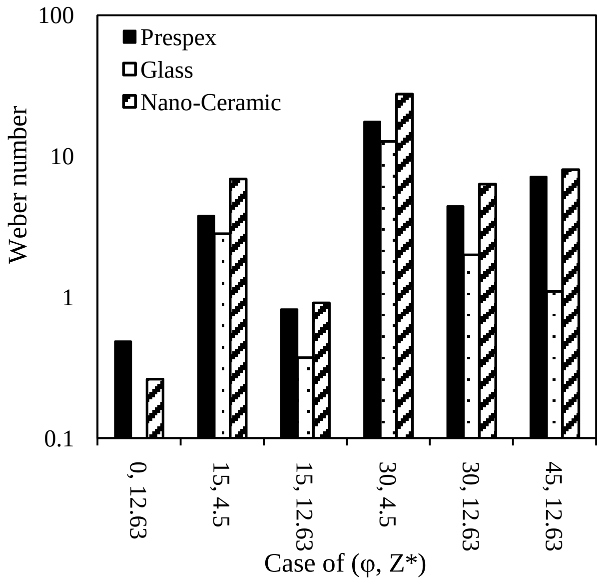


Figure 13: Ejection Weber number versus surface material, water drop and R_n =25.5*10^3*

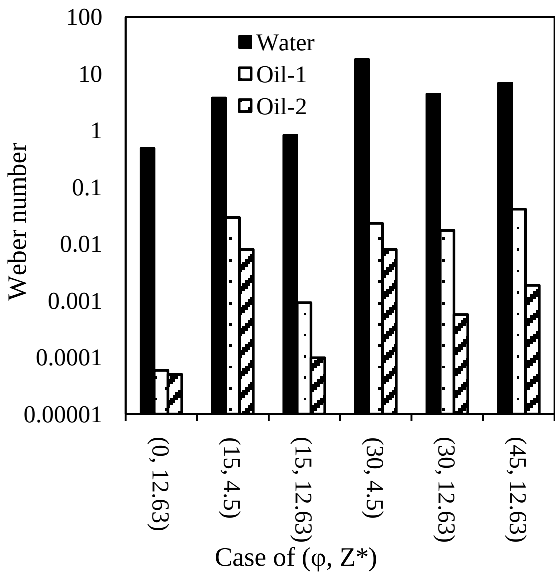


*Figure 14: Ejection Weber number versus liquid properties, perspex surface and R_n =25.5*10^3*

** Glass has no critical distance in (0, 12.63) case, the reason was previously mentioned above.*

Conclusions

The ejection behavior of a surface liquid drop by a gas jet has been examined for different liquids, surface materials, inclination angles and offset ratios. The behavior was assessed through the critical distance, response time of ejection and ejection speed. The studied parameters showed diverse effects on the drop ejection history. The following are the conclusions of this work

1- The ejection history is influenced by both parameters affecting wettability; the surface roughness of the contact surface and the liquid properties.
2- The wettability of liquid to the solid surface is dominating the ejection process, regardless the value of surface roughness. The high wetting case resulted in low ejection velocities even with nano-ceramic the smoothest.
3- The ejection history is affected by the liquid properties. The high viscous liquids are very slow compared to lighter liquids.
4- The critical distance is dependent on the liquid density. The lighter liquid is ejected at a lower distance.
5- The average velocity of drop is highly dependent on the liquid viscosity and surface tension. When both liquid viscosity and surface tension increase the drop velocity decreases.
6- The critical distance is nearly constant with all surface roughness values. Only about 5% change, in average, when referencing the case of perspex surface.
7- The response time is dependent on the surface roughness and the liquid dynamic viscosity. That any increase in the liquid dynamic viscosity or the surface roughness results in longer response time.
8- Every geometrical configuration of the inclination angle or the offset ratio results in a different critical distance and response time based on the effect of the impinging jet.

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