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Dynamic spreading of droplet on porous surface: Effect of droplet impact velocity and surface porosity

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ABSTRACT

Droplet spreading on porous surface has many applications in spray coating processes including coating of urea fertilizer. Coating uniformity is very important for effective function of slow release urea, which is achieved by good droplet spreading during spray coating processes. Limited studies are available on droplet spreading behavior on urea surface. Effect of droplet impact velocity and surface porosity on spreading of droplets on porous urea surface has been experimentally studied using high speed camera. Porous urea surface was made by solidifying molten urea. Droplet spreading on porous surface involves both spreading and penetration of the droplet. The relative rates of the two processes deepened on many factors like liquid viscosity, surface tension, impact velocity and surface porosity. Effect of droplet impact velocity and surface porosity has been studied on the droplet spreading behavior on porous urea surface. Increasing impact velocity increases both penetration into the porous surface and spreading of the liquid on the surface. Increased spreading is useful since it gives coverage during spray coating processes. Variation of porosity within the range of experiments does not show any significant effect on the droplet spreading behavior.

Keywords: Contact angle, wetting, porous surface, droplet impact velocity, spreading factor

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INTRODUCTION

Study of wettability of the surfaces has been studied since late 19th century [1]. The wettability of the surface has been extensively studied due to its role in many fields of engineering and science. In the beginning, droplet spreading behaviors of various liquids were investigated on flat surfaces by many researchers [2-5]. Major applications of droplet spreading behavior on flat surface include spray coating, spray cooling, fuel injection, high speed impact on turbines and aircraft icing [6-7]. Recently droplet spreading has been studied on super hydrophobic surfaces for various applications. Detailed review on studies of flat surfaces has been conducted by yarin [8] and C. Josserand [9].

With the progress in science and engineering, and introduction of new technology for material characterization, the boundaries of the study of droplet spreading behavior has also expanded. Porous materials were also being studied for the droplet spreading behavior. The droplet spreading on porous surface has even wider range of applications including ink jet printing to coating of porous materials, enhanced oil recovery and many other industrial processes. Droplet spreading on porous surface also has many applications in the field of agriculture like spreading of pesticides on soil and leaves and rain drop impact on soil [7, 10-11]. Another interesting application of droplet spreading in the field of agriculture is in urea coating. Urea is a widely used nitrogen based fertilizer. The issues associated with extensive use of urea and its increasing demand encouraged the researchers to produced slow release urea fertilizer. Most slow release urea is produced by fluidized bed coating. Coating uniformity of coated urea is very important for the functioning of slow release urea [12]. In spray coating process, coating film is produced by impact and spreading of many coating droplets one after another on the surface. Uniform coating can be accomplish by good spreading of droplets on the surface [13-14]. Knowledge of droplet spreading helps in attaining a uniform coating layer by highlighting the effect of liquid and surface properties on the spreading process.

Droplet spreading behavior on porous surface is quite different than spreading on solid surface. Droplet spreading on porous surface involves both spreading on the porous surface and penetration into the porous solid. The relative rates of the two processes depend upon many factors like liquid viscosity, surface tension, droplet impact velocity, surface porosity etc [8, 15]. Complicated spreading situations are yet not well understood [16-17]. Capillarity is the driving force for the penetration of the fluids into the substrate [18-19]. The penetration is characterized by a capillary suction acting across the wetting front, which may be regarded as measure for mean pore size [19]. Rapid deceleration of droplet in the impact region occurs thereby creating an increased pressure, and this elevated pressure is responsible for radial projection of liquid. Droplet spreads gradually but soon velocities start to decrease due to viscous effects [5, 18, 20]. Droplet spreading behavior is affected by the properties of liquid like viscosity, surface tension, density; by the properties of surface like wettability, porosity and roughness; and also by the process parameters like droplet size and impact velocity. Penetration of liquid into different kind of porous surfaces follow different pattern. Limited studies are available on the droplet spreading behavior of urea surface [21-22]. In the current study, effect of porosity and impact velocity has been studied on droplet spreading behavior on urea surface.

MATIERIALS AND METHODS

Materials

Urea from PETRONAS Fertilizer Kedah was used for all the experiments. The porous surface consists of solidified urea. Porous urea surface was prepared by melting urea prills at a temperature of 140^0 C. The molten urea was then poured into a cylindrical plastic mould. The urea melt was allowed to cool for a period of two hours. The solidified urea pellets were then taken out of the mould and stored in air tight plastic bags for the purpose of characterization and experiments. The pellets were 25.4 mm in diameter and 6.35 mm in height. The porosity of the urea surface was measured by He-Porosimeter from VINCI Technologies FRANCE at a pressure ratio of approximately 1.4 bar. The He-porosimeter works on the principle of Boyle-Mariotte's Law. Moto engine oil was used as test liquid because of its non reactive nature for urea surface. Its viscosity was reduced to 20 cp to match the viscosity of coating material by adding benzene into it. The surface tension of the liquid was 26.65 mN/m and density of the sample was 0.8 g/cm^3.

Droplet spreading experiments

Droplets of the liquid were produced with the help of medical syringe. The droplet size was 2 ± 0.1 mm. The droplet impact velocity was changed by changing the height of the syringe from the substrate. The droplet velocity was measured with the help of camera. The calibration of the camera was carried out for the droplet velocity determination. The droplet spreading was recorded with the help of Phantom high speed camera (Miro M320S) at a resolution of 768×400 pixels and 1700 frames per second with an exposure time of 70 micro seconds. The videos were recorded for a period of 8 seconds. The time of recording was limited by the storage capacity of the camera. The experimental setup is shown in figure 1. The light source was placed exactly opposite to the camera lens. The level of the camera was adjusted so that it is parallel to the solid surface. The experiments were repeated three times and the average results have been reported. Images from recorded video were extracted for data analysis. Images were extracted at an interval of 0.1 sec for the first second after impact since drop shape is changing at a very fast rate in the start. After 1 sec, the images were extracted at an interval of 1 sec.

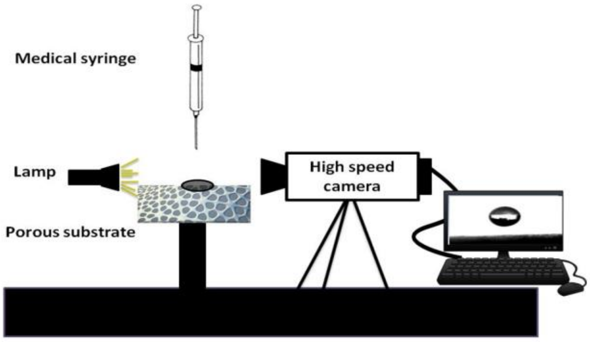

Figure. 1. Schematic of experimental setup to capture droplet spreading

Image Analysis

Value of droplet diameter at the time of its contact with the substrate is designated as D_o. Time t= 0 sec is also defined at this very moment. The width of droplet base has been normalized using the initial droplet diameter i.e. $D=D_o/D_t$ where D is spreading factor, while D_o is the initial diameter of the droplet and D_t is width of droplet base at any given time t.

Droplet images were extracted from the recorded video at the required point of time. Edge detection algorithm namely 'Edge Hipass 3-by-3' was applied for edge detection to get a clear picture for contact angle measurement. Edge Hipass enhances 3-by-3 pixel translation areas or edges in an image, enhancing the high-frequency detail. Contact angle was measured using ImageJ software which utilizes low-bond axisymmetric drop shape analysis (LA-ADSA) method which is based on fitting of Young-Laplace equation to the image data [23].

The droplet volume over the porous surface has been measured from the side view images to estimated the rate of penetration of the liquid into the porous structure. The rate of penetration of the droplet into the surface was determined by calculating the projected surface area of the droplet on the porous surface over time. The projected surface area of droplet in the images was measured in pixels by using the image processing toolbox of MATLAB R2012. The numbers of pixels were calculated after determining the gray scale threshold for every image. The faster the projected surface area of the droplet decreases with time, the higher is the penetration rate of the droplet into the surface.

RESULTS AND DISCUSSION

Spreading of droplet on porous surface

Droplet spreading on porous surface is somewhat different than spreading on solid surface. While spreading on solid surface, droplet spreads over the period of time, the contact angle keeps on decreasing while the spreading factor increases. In spreading on porous surface, as the high velocity droplet hits the porous surface, it starts to spread on the porous surface and at the same time, it penetrates into the porous zone. Either of these two processes (i.e. penetration and spreading) is faster than the other depending upon the porosity of the substrate, impact velocity of the droplet and the surface tension of the liquid [5, 18-20, 24].

In the current study, high impact velocities have been employed. As the droplet hits the surface, the droplet shape quickly transforms into a hemisphere and spreads very quickly at the surface. The expansion is very fast at the start of the experiment due to the high kinetic energy of the droplet. After few seconds, the expansion slows down while the penetration continues for some time. Temporal variation of the droplet shape with respect to time is shown in figure 2. Droplet spreading process is very fast at the start of the experiment so the data has been reported at an interval of 0.1 sec for the first 1 second. Afterwards, droplet spreading gradually slows down and hence the data has been reported at an interval of 1 second.

Figure 2: Temporal variation of droplet shape after impact on the surface

Effect of droplet impact velocity on Droplet spreading behavior

The droplet spreading behavior is mainly characterized by spreading factor, droplet contact angle with the surface and penetration rate of the droplet. The rate of penetration of droplet into the porous surface can be estimated by measuring the volume of the liquid left above the porous surface at any point of time. Advanced non destructive techniques are also available for some applications [25-27].

In the current study, effect of droplet impact velocity has been studied on droplet spreading behavior over porous urea surface. Droplet spreading behavior has been studied for droplets with three different impact velocities i.e. 1 m/s, 2 m/s and 3 m/s. the samples of urea used for the experiments were having same porosity i.e. 21% as measured by He-Porosimeter. When the droplet hits the porous surface with high impact velocity, the kinetic energy of the droplet causes the droplet to spread laterally over the porous surface. This lateral expansion rapidly increases the spreading factor. This can be seen from the exponential increase in the value of spreading factor in first one second of the droplet spreading process for all three impact velocities as shown in figure 3. However, after one second of droplet impact, the spreading process relatively slows down, though it continues till the end of the experiment. It is clear from the figrue 3 that droplet spreading increases as the droplet impact velocities area increased. Droplet with an impact velocity of 1 m/s shows least spreading while droplet with impact velocity of 3 m/s shows maximum value of spreading factor. J. B. Lee et. al. also observed similar phenomenon [28].

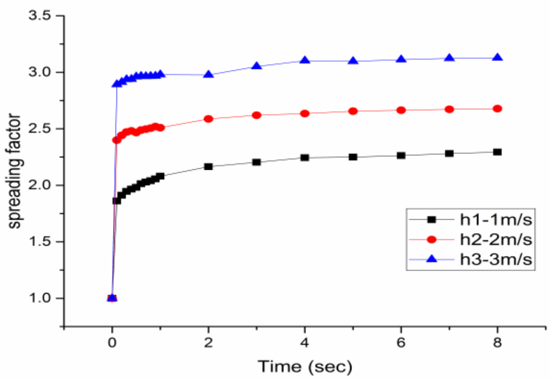

Figure. 3: Spreading factor vs time (s) for various impact velocities

Droplet spreading behavior is also characterized by the contact angle of the droplet with the surface. Contact angle of the droplet decreases as the droplet spreads over a surface. When a droplet is spreading over porous surface, the decrease in contact angle is a combined effect of droplet spreading and penetration into the porous surface. The results show that contact angle decreases at a very fast rate at the start of the experiments until approximately 2 seconds as shown in figure 4. The rapid decrease in contact angle is because of both lateral displacement of liquid above the substrate surface and droplet penetration into the surface. Afterwards, contact angle still continues to decrease but at a slower pace. the contact angle decreases as the impact velocity of the droplet increases which means more spreading and penetration. The contact angle values less than 90^{o} shows a dynamic wetting behavior of liquid over the porous surface [28].

The droplet penetration into the porous surface can be observed by looking at the decrease in the droplet volume above the porous surface which in this case is represented in terms of normalized surface area of the droplet from the pictures of droplet above the surface. This normalized surface area is measured in terms of number of pixels as explained in the methodology section. It is clear from figure 5 that the droplet projected area and hence droplet volume above the surface decreases sharply for one second after the start of spreading process. It drop volume continues to decrease at a relatively lower rate for next 5 seconds as shown in figure 5. A combined analysis of variation of droplet volume above the surface (Figure 5) and variation of spreading factor of the droplet (Figure. 3) shows that the spreading factors increases sharply for 2 seconds while droplet volume decreases sharply for only one second after the impact. Moreover, the spreading factor continues to spreads, on a slow pace though, till the end of the experiment showing that the droplet is still spreading over the surface. However, the droplet volume above the surface has stopped decreasing after 6 seconds showing no further penetration into the porous substrate. This shows that droplet spreads and penetrates at a very fast rate at the start of the experiment. High spreading rate of the droplet is because of high momentum of the droplet which is being dissipated in lateral displacement of the droplet. The same momentum is also pushing the droplet liquid into the porous surface. Along with this push from outside, the capillary pressure within the porous surface is pulling the liquid inside. Hence facilitated by pull from inside and push from outside, the droplet liquid penetrates into the porous surface. The droplet penetration slows down as the porous surface just below the droplet base becomes saturated with the liquid [29]. This makes the penetration of the liquid difficult. Ultimately penetration of liquid into the porous media stops after 6 seconds of impact which is clear in Figure 5 where the normalized projected area stops decreasing after 6 seconds for all three impact velocities. Nevertheless droplet spreading continues after that. This is mainly because of the high impact velocity. At the same time, a layer of liquid which has penetrated into the porous surface will facilitate the forward motion of the liquid above the surface. Hence the liquid spreads over the surface. That is why droplet spreading continues longer then droplet penetration.

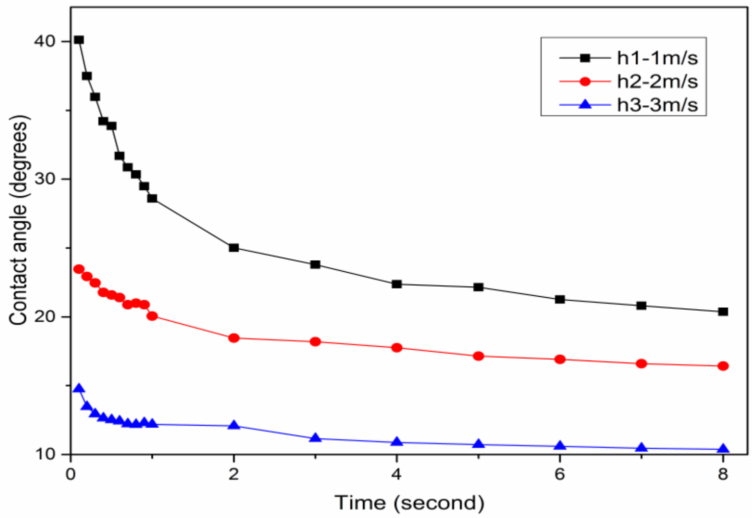

Figure. 4. Variation of contact angle vs time (s) for various impact velocities

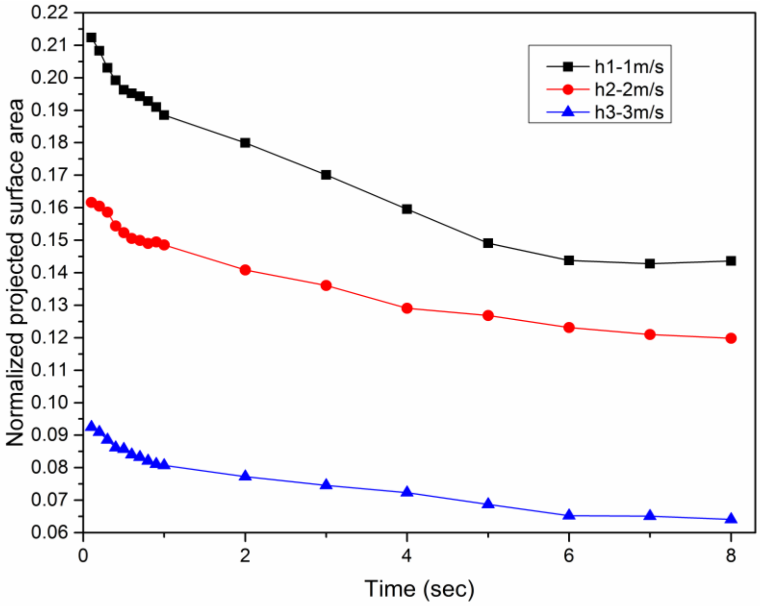

Figure 5: Effect of impact velocity on droplet penetration rate

Effect of Reynolds number

Reynolds number is the ratio of inertial force and viscous force. During the process of droplet spreading on porous surface, both the forces pay their roles. Inertial forces help the liquid spread over the surface. while viscous forces resist penetration of the liquid into the porous structure [18]. At high Reynolds number, inertial forces are stronger then viscous forces, and they dominate the spreading dynamics. When the kinetic energy has been dissipated to a great extent, effect of viscous forces comes into play. Very low Reynolds number, viscous forces not only resist the liquid penetration but also resist the lateral movement of the liquid above the surface.

Effect of Reynolds number on droplet spreading behavior has been studied. Figure 8(a) shows the plot of final contact angle with Reynolds number in the experiments. Final contact angle linearly decreases with increase in Re no. As the Reynolds number increases, the momentum of the droplet increases. The increases momentum is dissipated in both vertical and horizontal direction i.e. spreading and penetration. Since the increased Reynolds number is supporting both spreading and penetration of the droplet, the contact angle is decreasing, spreading factor is increasing and drop volume above the surface is decreasing. For achieving a good coating film, the droplet needs to give maximum coverage area. This can be achieved with higher spreading factor values. However, care should be taken while increasing impact velocity since very high impact velocity can cause splashing.

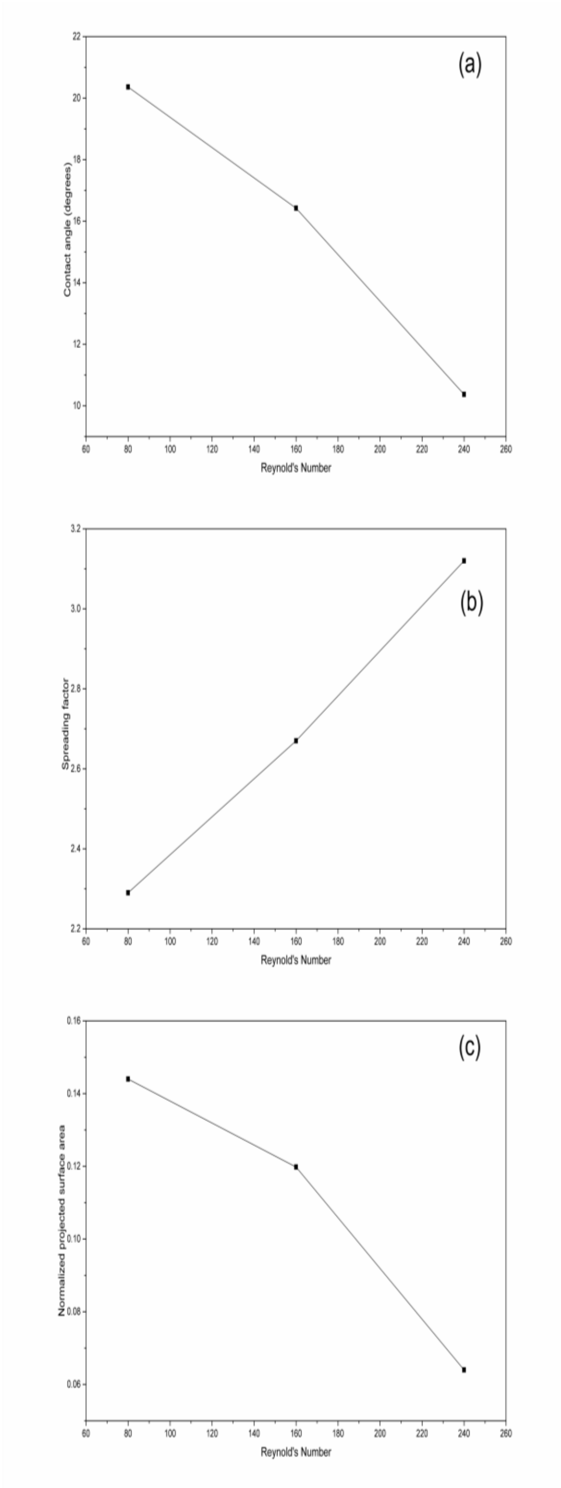

Figure 6: Effect of Reynolds number on (a) contact angle (b) spreading factor (c) Normalized projected surface area

Effect of surface porosity on droplet spreading

The effect of surface porosity on droplet spreading has been experimentally studied under given conditions. Three samples of different porosity has been used. The porosity of the samples has been measured with the help of He-porosimeter as mentioned in the methodology section. The plots of contact angle (Figure 7) and spreading factor (Figure 8) shows that the final value of contact angle and spreading factor is almost the same in the given porosity range. It can be concluded that for high speed impact velocity, the variation of porosity of surface in the given range has no significant impact. Usually droplet penetration increases with increased in the porosity of the sample. However, when talking about the penetration of liquids in the porous surface, many factors are at play. Porosity measurement method influences the porosity values obtained. Some samples when tested with different methods give different porosity values. Most appropriate method is to measure the porosity of the surface with the test liquid. However, test liquid has very high viscosity and cannot be used for porosity measurement. Therefore, It can be concluded that for high speed impact velocity, within the studied range of porosities, the variation of porosity of surface has no significant impact..

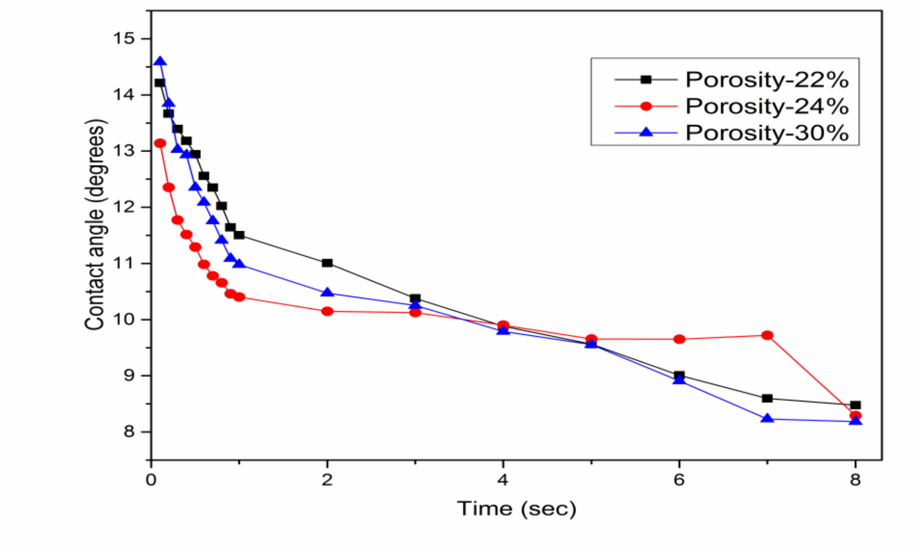

Figure 7: Effect of surface porosity on spreading factor

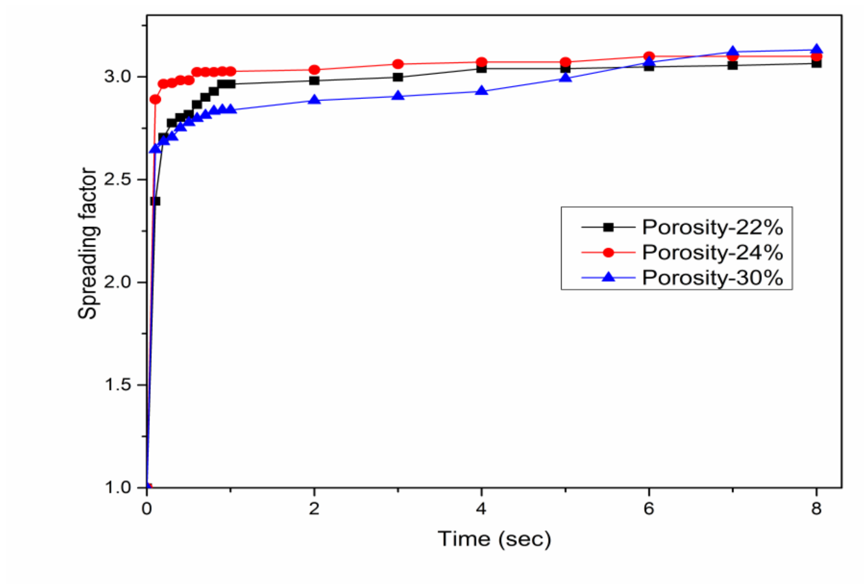

Figure 8: Effect of porosity on contact angle

CONCLUSION

The effect of droplet impact velocity and surface porosity has been studied on droplet spreading behavior on urea surface. As the droplet impact velocity increases, the spreading of droplet over the surface and penetration into the surface increases. However, the droplet spreading continues longer than droplet penetration because the surface below the droplet base becomes saturated with liquid and further penetration becomes slower after some time. This liquid below the droplet base however facilitates the droplet spreading over the surface and hence droplet spreading continues longer then droplet penetration. There is no significant change in droplet spreading behavior for a variation in porosity. Final values of contact angle and spreading factor are same regardless of the porosity of the sample. This is because of the porosity measurement method and the narrow range of porosities used in this study.

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