

Absorption of Millimeter-Sized Droplet by Nylon Powder

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ABSTRACT

Droplet impact on powder materials is a ubiquitous phenomenon in nature and engineering technologies. An important aspect of droplet-powder interaction is the absorption of liquid droplet by powder substrates due to capillary force. In this study, we have investigated the phenomenon of absorption of multiple solutions into the substrate material of nylon powder PA2200. Absorption of droplet by powders does not always occur even though a liquid may partially wet the surface of the powder substrate. The critical surface tension values for nylon powder bed having different porosities are obtained by experiments and discussed in detail. Our study shows that smaller surface tension or smaller porosity leads to faster absorption. We discuss the effects of surface tension and porosity of powder layer on the absorption.

Keywords: droplet, absorption, nylon powder, Zisman's Plot, additive manufacturing

1 THEORY

1.1 Critical Surface Tension

A common subject in the absorption studies is whether a given liquid be able to completely wet the given solid or not and the answer to this is in the term Critical Surface Tension (CST) which is defined as the maximum surface tension value above which the liquid cannot wet the given solid [1]. To find out the CST for a given powder substrate, we employ the Zisman's Plot which is a relation between $\cos(\theta)$ and surface tension (where θ is the contact angle made by fluid over the substrate) [2], [3].

1.2 Absorption and Evaporation

The flow through porous media by considering capillary tubes is one of the most common approaches to estimate the drop absorption analytically [4]–[6]. The driving force in such wicking phenomena of droplet on powders is the capillary force. There are two traditional approaches in calculation of absorption rate: the Washburn equations and using Darcy's Law [7]. The Darcy's Law describes the momentum equation of flow through porous media with low flow velocity, which relates the volume averaged velocity (i.e. superficial velocity) with pressure gradient along flow direction as following [8]

$$U = K_d \frac{\Delta p}{\mu \cdot L} \quad (1)$$

where, U is the velocity, coefficient K_d is permeability, μ is the dynamic viscosity and L is the length of the powder bed. Permeability K_d is usually a function of porosity ϵ , geometrical structure of porous media including tortuosity [9].

The capillary pressure difference Δp , which is approximated using the Young Laplace equation, is the driving force for the imbibition as [10],

$$\Delta p = \frac{2\sigma}{r} \quad (2)$$

where, σ is the surface tension, r is the radius of capillary or hydraulic radius. The contact angle of liquid, inside the capillary tube, getting absorbed due to capillarity is assumed to be zero making $\cos(\theta) = 1$.

If the powder substrate is viewed as a bundle of capillary tubes, the velocity of liquid flowing through capillary from Poiseuille's law as [8],

$$v = \frac{dx}{dt} = \frac{r^2 \Delta p}{8\mu x} \quad (3)$$

where x is the depth of travel by the liquid droplet into the powder, r is the radius of capillary or hydraulic radius, t is time. Δp is the capillary pressure difference and can be estimated from equation 2. For millimetre-sized droplets, the Bond number $Bo = \rho g D^2 / \sigma$ (where ρ , g , D is density, gravity, and droplet diameter, respectively) reveals that the gravity force can be ignored. On integrating Eq. 3, we can obtain the relationship between the position of advancing meniscus x and time t as,

$$\frac{x}{r} = \sqrt{\frac{\sigma t}{2\mu r}} \quad (4)$$

Eq. 3 can be used to calculate the volume flow rate [8]. If we assume the contact area between droplet and powder is constant during absorption, the droplet volume outside the powder substrate can be derived as,

$$Q(t) = Q_0 - \pi R_0^2 \epsilon \sqrt{\frac{\sigma r t}{2\mu}} \quad (5)$$

where $Q(t)$ is the volume of the drop at the given time, Q_0 is the initial volume, R_0 is radius of the contact area of droplet on the powder at time $t=0$. The term ϵ is introduced in the volume flow rate through porous media as porosity is the ratio of free space to solid space. Hence, ϵ times volume flow determines absorption through capillarity in the porous medium [8].

In order to use equation 5, we need to determine the capillary radius r (hydraulic radius) for a given substrate. This is given by the Kozeny equation [4], [5],

$$r = \frac{\epsilon D_p}{6 * (1 - \epsilon)} \quad (6)$$

where, D_p is particle size and ϵ is powder bed porosity. The evaporation phenomenon of a sessile droplet is studied extensively in the case of total evaporation [11], [12]. The equation for rate of evaporation can be derived from the energy balance equation as [13], [14],

$$N_c = \frac{A(\Delta T) h_c}{\lambda} \quad (7)$$

where N_c is evaporation rate of droplet, A is the droplet surface area, ΔT is temperature difference of droplet and surrounding, h_c is the convective heat transfer coefficient and λ is the latent heat of vaporization of the fluid. The evaporation rate directly relates to the surface area, difference in the temperature and the convective heat transfer coefficient, whereas it relates inversely to the latent heat vaporization.

In addition, we can determine the convection coefficient h_c by the following empirical relation [11]

$$\frac{D h_c}{K_t} = 2 + 0.6 * \left(\frac{D v \rho_a}{\mu_a} \right)^{0.5} * (Pr)^{0.33} \quad (8)$$

where D is the initial diameter of droplet, K_t is the thermal conductivity, μ_a and ρ_a are viscosity and density of surrounding air, v is the velocity of air moving around the droplet surface and Pr is the Prandtl number. This method of determining evaporation rate is based on the energy balance principle [13], [15].

2 RESEARCH METHOD

In this study, we used the instrument Ramé Hart (RH) Goniometer and the accompanying software DROPImage to calculate the contact angle, surface tension, height, width, radius and volume of the drop. The diameter of the needle being used for drop formation is 0.508 mm.

To test the variation of surface tension, contact angle and absorption rates of liquids with respect to porous substrates, five aqueous solutions of isopropyl alcohol were prepared. The density and dynamic viscosities of all these solutions are calculated analytically using the molar mass of

isopropyl alcohol in the solutions [16]. Aqueous solutions of 6.5%, 7%, 7.5%, 8% and 9% by volume of isopropyl alcohol are prepared.

To study the effect of porous structure of powders on absorption, four different samples of porosities were prepared using manual compacter device with clamping arrangement and torque wrench with defined consistent load. The nylon powder PA2200, with particle size of $56 \pm 3 \mu\text{m}$, bulk density 0.45 gm/cm^3 and the density when laser sintered is 0.93 gm/cm^3 is used (data from material data sheet by provider).

With the known volume of the powder in the compacter and measured weight, densities for four compactations were measured. Accordingly, we use $\epsilon = 1 - (\rho_{\text{bulk}}/\rho_{\text{compact}})$ for getting the porosity, where ρ_{bulk} is the loose powder density ρ_{compact} is the compacted powder density [5]. The porosities used are $\epsilon = 0.28 \pm 0.02$, 0.34 ± 0.02 , 0.38 ± 0.02 and 0.41 ± 0.02 .

3 RESULTS AND DISCUSSION

3.1 Results with solutions on porous substrates

Four substrates with different porosities were tested with water and five aqueous solutions of isopropyl alcohol. De-ionized water showed hydrophobic nature with respect to the nylon powder substrates. We anticipated high surface tension value of water as one of reasons for it not being able to wet the powder substrate [4]. When aqueous solutions of isopropyl alcohol were tested, we saw reduction in the contact angles (see Table 2). When the liquid droplet is not absorbed by powder substrate, an equilibrium contact angle can be found using the goniometer.

To explain the absorption was the dominating effect than evaporation, we calculated the evaporation time for the droplets in the working conditions of lab (room temperature 25°C and liquid temperature of 22°C), knowing there is only free air convection. Table 3 states the time required for pure evaporation for respective liquid using the *equation 7 and 8*. It is interesting to note from Table 2 that for non-absorption cases, the equilibrium contact angle reduces with increase in compaction. Furthermore, the contact angle decrease is also observed as surface tension of the liquids goes on decreasing. It seems that even though the loose nylon powder acted as hydrophobic surface for water, the wettability property were boosted when the same powder was compacted [4]. The decrease in the contact angles may be attributed to the increased capillarity effect. With the compaction of the powder, there is decrease in porosity and hence in capillary radius r given by *equation 6*.

3.2 Critical Surface Tension for different porosity

From the experimental measurements, the relation between $\cos(\theta)$ and surface tension for a given powder

substrates can be plotted in Figure 1. The graph is often

referred to as the Zisman's Plot [1], [9].

Table 1: Properties of different liquids used in the experiments.

Solution	Density (gm/cm ³)	Dynamic Viscosity (cP)	Mean Surface Tension (mN/m)
De-ionized Water	0.998	1.002	72
6.5 % Isopropyl Alcohol	0.9888	1.1075	49
7 % Isopropyl Alcohol	0.9882	1.1258	47
7.5 % Isopropyl Alcohol	0.9876	1.1438	45.5
8 % Isopropyl Alcohol	0.9871	1.1607	43
9 % Isopropyl Alcohol	0.9858	1.2022	41.7

Table 2: Contact Angles of Test Liquid on porous substrates

Solution	Mean Contact Angle θ in degrees			
	$\epsilon = 0.28 \pm 0.02$	$\epsilon = 0.34 \pm 0.02$	$\epsilon = 0.38 \pm 0.02$	$\epsilon = 0.41 \pm 0.02$
De-ionized Water	117 ^o	122 ^o	133 ^o	136 ^o
6.5 % Isopropyl Alcohol	76 ^o	89 ^o	98 ^o	125 ^o
7 % Isopropyl Alcohol	74 ^o	93 ^o	96 ^o	114 ^o
7.5 % Isopropyl Alcohol	9 ^o	58 ^o	66 ^o	105 ^o
8 % Isopropyl Alcohol	Absorbed (~1.3 seconds)	Absorbed (~2.2 seconds)	Absorbed (~2.3 seconds)	102 ^o
9 % Isopropyl Alcohol	Absorbed (~0.8 seconds)	Absorbed (~0.9 seconds)	Absorbed (~1.1 seconds)	100 ^o

Table 3: Evaporation rate and time for average droplet volume 7.2 mm³

Liquid	Heat of Vaporization (kJ/kg)	Evaporation rate (gm/s)	Time for evaporation (s)
Distilled Water	2270	1.2506×10 ⁻⁶	5746
Isopropyl Alcohol	665	4.2685×10 ⁻⁶	1327

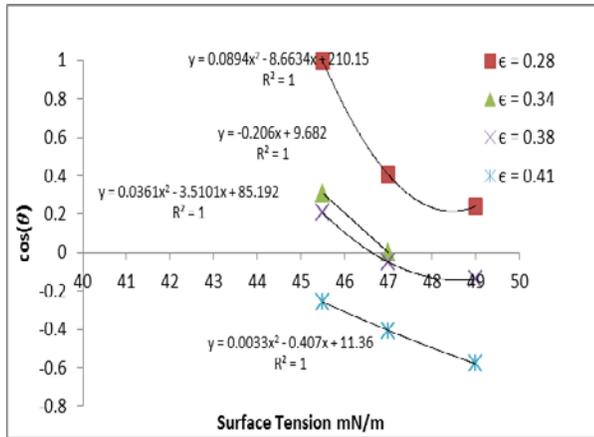


Figure 1: Zisman's Plot for droplet of different liquids on powder substrates with $\epsilon = 0.28, 0.34, 0.38$ and 0.41 . The solid lines in the figure are curve fitting using the 2nd-order polynomial function.

When we extrapolate these curves to intersect $\cos(\theta) = 1$, we can estimate the critical surface tension or surface free energy for respective substrate. Our data indicate that more compaction of the powder material allows a liquid of a higher surface tension to be absorbed by powders.

From our test results, we can infer that any fluid with surface tension above these threshold surface tensions would not be able to wet the respective nylon powder

substrates. For example, for powder substrate of $\epsilon = 0.38$, 8% isopropyl alcohol of surface tension $\sigma = 43$ mN/m was absorbed, whereas 7.5 % isopropyl alcohol of $\sigma = 45.5$ mN/m was not absorbed at all despite that the contact angle in this case is less than 90° .

Table 4: Critical Surface Tensions for different substrates

Nylon powder PA2200 substrate porosity	Critical Surface Tension for complete wetting
$\epsilon = 0.28$	~45 mN/m
$\epsilon = 0.34$	~44 mN/m
$\epsilon = 0.38$	~43 mN/m
$\epsilon = 0.41$	~40 mN/m

3.3 Comparison of Analytical and Experimental Absorption Result

With the absorption theory discussed in section 1.2, we can compare the analytical predictions of volume to the experimental result. We adopted the capillarity model established by Middleman [8] to track the unabsorbed volume of droplet in the drop wicking in the porous medium. Results for 8 % and 9% Isopropyl Alcohol on substrates of $\epsilon = 0.28$ is showed in Figure 2.

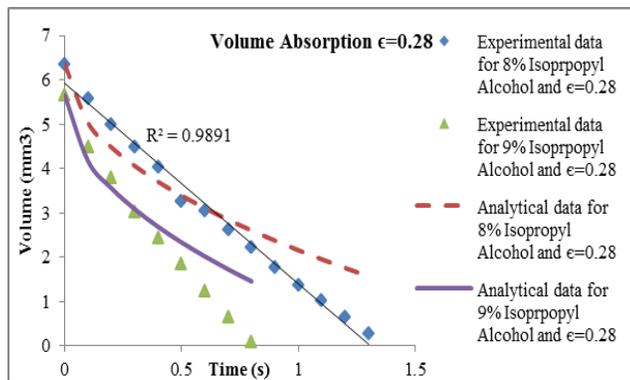


Figure 2: Absorption of droplet of 8 % and 9% Isopropyl Alcohol on substrates of $\epsilon = 0.28$.

These results show that absorption equation derived by Middleman et al [8] do not have good agreement for porous substrates and aqueous solutions of isopropyl alcohol.

4 CONCLUSION

With multiple aqueous solutions of isopropyl alcohol we have tested the wettability results for nylon powder substrates. An important phenomena of change in wettability and critical surface tension due to change in porosity of same powder bed is presented. We have discussed how the most widely known analytical model for volume absorption disagrees with the experimental data. The experimental data proves that volume absorption rate for aqueous solutions into the porous substrate vary inversely with respect to the porosity and surface tension.

A simple model of determining the critical surface tension is introduced for applications in manufacturing sector. We studied the Zisman's plot in determining the critical surface tension for absorption. For any aqueous fluid of surface tension equal to and below the critical value, it will be absorbed by the respective substrate of given porosity, whereas those fluids with higher surface tension values would not get absorbed for same respective substrates.

We learn the influence of surface tension for a liquid to wet the surface and to get absorbed. We also learn that compact porous substrates have higher wettability.

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