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DROPLET IMPACT AND PENETRATION ON A LINE OF CAPILLARY TUBES

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ABSTRACT

Impact and penetration of a liquid droplet on a substrate having a line of parallel capillary openings drilled along its thickness is experimentally studies. Different regimes of droplet penetration are identified. At low impact velocities, the droplet impacts on the substrate, spreads, and penetrates into the substrate mainly due to the capillary action in each tubular hole. At higher impact velocities, the droplet impacts on the substrate, spreads and penetrates due to the droplet inertia, and then penetrates further due to the capillary action. Threshold velocities for liquid penetration into capillary tubes are identified. Two penetration regimes, capillary and inertia driven regimes, have been studied extensively for a range of parameters related to droplet impact on a line of parallel capillary openings.

Index Terms—Droplet impact, parallel capillary tubes, penetration, liquid spread.

INTRODUCTION

Droplet impact on porous substrates occurs in a variety of fields such as in ink jet printing where an ink droplet is impacted on the surface of a porous paper, in thermal spray coating of porous substrates, and in rainfall on soil. The impact of a liquid droplet on a porous substrate is a combination of a droplet impact on a solid non-porous substrate and capillary penetration of liquid in porous media. Although the impacts of a liquid droplet on a solid substrate, as well as liquid flow through porous media are individually studied extensively, there are very limited studies on their combined effects.

When a droplet impacts of a solid surface, it spreads radially until it reaches a maximum spread diameter. The droplet may retract and after several oscillations reach an equilibrium shape on the top of the substrate; it may splash and breakup into small droplets; or it may bounce off the surface [1-3]. The maximum spread diameter and the final outcome of the droplet impact depend on the droplet impact velocity, droplet size, liquid and surface properties including surface tension, surface roughness and wettability [4-8]. Other effects, such as bubble entrapment during the impact [9], solidification and viscosity changes in the liquid [10], and hydrophobic and hydrophilic surface effects [11-15] have also been considered. There are also a number of modeling studies on the droplet impact [16-19] showing the details of the fluid and temperature fields inside the droplet during the impact process. Studies related to the droplet impact and penetration into porous materials is scarce [20-22]. Most of these studies were focused on the imbibitions of liquid due to the capillary pressure difference. Delbos et al. [23] experimentally investigated the penetration of liquid into a capillary tube using the initial kinetic energy of an impacting droplet. They studied the impact of liquid drop on a single hole in the scale of drop size and evaluated different regimes for penetration based on hydrophobicity of surface. Chandra and Avedisian [24] studied the dynamic aspect (deformation and spreading on a surface) of an n-heptane droplet impingement onto a porous ceramic surface with surface temperatures ranging from 22 to 220 °C.

Yue and Renardy [25] proposed a model for the penetration of a non-wetting liquid drop into a porous medium. The liquid drop was considered to be approaching an exposed pore along the axis of symmetry. Five penetration regimes based on static contact angle and initial drop radiuses were identified. Studying the penetration on single hole neglecting the effect of inertia and capillary, divided to 5 regimes of (I) penetration without spreading, (II) penetration with spreading, (III) penetration with spreading that relies on the initial transient, (IV) non-penetration with spreading, and (V) non-penetration without spreading. The scale of this study is related to penetration when it's not small due to the droplet size.

In the present study, we experimentally investigate the impact on and penetration into a line of parallel-holes drilled through a substrate. The main target of this work is to combine physics of capillarity with that of droplet impact.

1 Experimental System

A schematic of the experimental setup used in this research is shown in Figure 1. A syringe pump (NE-1000, New Era Pump Systems Inc., USA) was used to dispense one droplet of water from a needle onto a substrate with a line of parallel-holes drilled in it. The syringe containing the distilled water was secured onto the pump and a plastic tube was used to transfer the liquid from the syringe onto the needle. The needle was attached to a height-adjustable experimental rig that allowed us to vary the height of the needle with respect to the substrate. The experimental rig consisted of three pillars with a threaded middle pillar which allowed for height adjustments using a hand-operated wheel on top of the structure. The base of the rig was screwed into the optical table. The substrate was cleared from the optical table using spacers. It was ensured that the spacers themselves did not restrict the bottom of the parallel holes.

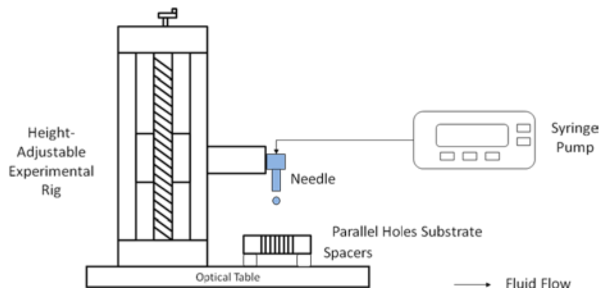

Figure 1 : Schematic of the experimental system

The substrate was made from poly-carbonate with a length of 0.6”, width of 0.5” and height of 0.3”. At the center of the width of the substrate seven through-holes each with a diameter of 300 µm and distance of 300 µm from one another were drilled in a straight line. The water droplet is impacted at the center of the line of holes. Gage 17 and 34 needles were used which gave us droplets with diameters of 3.2 mm and 2.0 mm. The droplets were released from 1, 3 and 5 cm heights. The droplet impact, spreading and capillary penetration into the holes was observed using a high speed camera (FASTCAM SA5, Photron, USA). The video was taken at 4000 frames per second, 1024x1024 pixel resolution and 40.7 µs shutter speed. In a separate set of experiments designed to see the contact angle in the holes, higher magnification videos were taken at 2000 frames per second, 1024x1024 pixel resolution and 40.7 µs shutter speed.

2 RESULTS AND ANALYSIS

Figure 2 shows the impact sequence of a droplet on the substrate having 7 parallel holes. Droplet diameter in these cases is 3.2mm and droplet is released from three different heights of h= 1mm, 3mm and 5mm from the bottom of the formed droplet at the nozzle.

At 1mm height (Fig. 2-a), the impact energy is low and the droplet does not penetrate into the substrate upon impact. The penetration starts at approximately 7ms after impact. At this time (t=7ms), the droplet has already spread to about 75% of its maximum spread diameter. After 12ms from impact, the droplet rebound process starts. The rebound process tends to pull the liquid back, stopping or even retracing the penetration process. The rebound process is completed at about 18ms after the impact, after which time the penetration process restart at a lower rate. The images show that the penetration in each capillary hole is different than the other. This is mainly due to the delay in the start of the penetration for each hole.

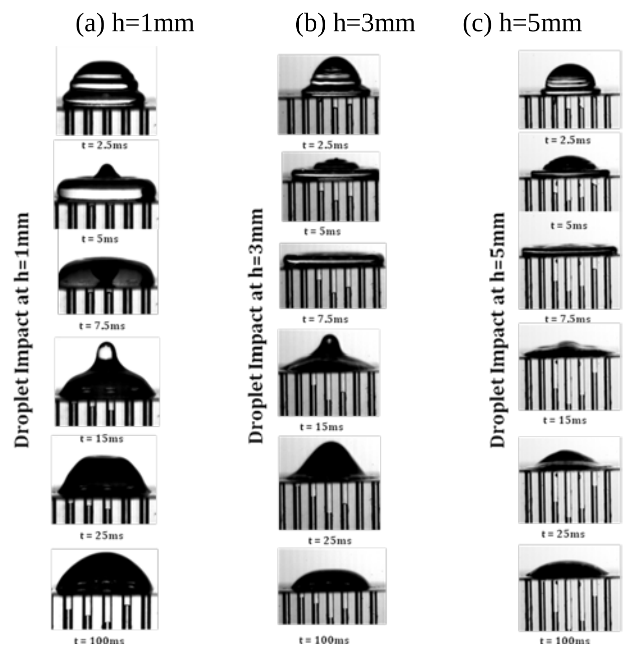

Figure 2: Water droplet impact and penetration for a 3.2mm droplet from 1, 3 and 5 mm heights.

The sequence of a droplet impact and penetration released from a height of 3mm is presented in Figure 2-b. In this case, due to the higher droplet inertia, the penetration starts at the first moment of impact. Liquid keeps penetrating with the same rate until t=6.5ms. At this time, the droplet has reached its maximum spreading diameter. Then, the liquid penetrates steadily but at a lower rate. Figure 2-c shows the impact process of a droplet released from a height of 5mm from the substrate. The penetration process is seen to starts at the first moment of impact but it proceeds at a higher rate with respect to the 3mm height case. At t=8ms the droplet reaches its maximum spreading, at which point the penetration rate reduces. The droplet goes through an oscillation process from t=10ms up to t=100ms, however, the penetration rate remains almost constant. At this height of impact, penetration pauses while droplet starts the rebound process and then it continues with lower speed.

Two types of penetration can be identifies: fast penetration, which occurs right at the time of impact, and slow penetration which follows that. The initially fast penetration is governed by the droplet impact inertia, thus is an inertia driven penetration. The slow penetration is governed by the capillary actions inside the holes and pores, and thus is a capillary driven penetration. Penetration of water into the centre capillary hole for impact heights of 1, 3 and 5mm is plotted in Figure 3. The time scales of fast and slow penetrations can be clearly identified.

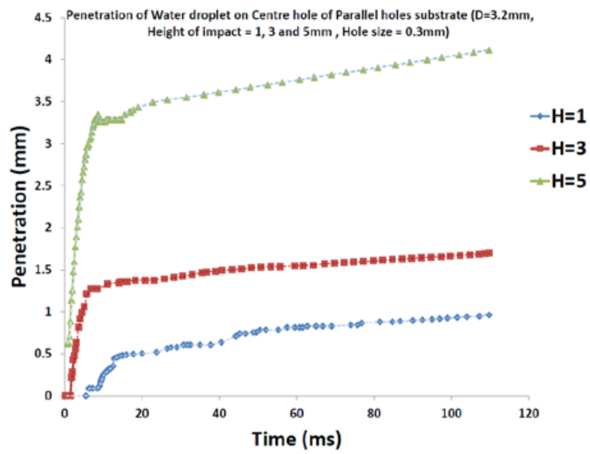

Figure 3 : Penetration history of impacted droplet on centre hole for three different heights

Similar penetration types are observed for the other holes on the substrate. The only difference is that the penetration for each hole starts at different times. Figure 4 represents penetration at three different impact heights of 1, 3 and 5mm onto the centre, right and left holes. From a 1mm height, inertia driven penetration starts with time difference which is due to small amount of impact energy. Capillary driven penetration is also in small difference of pressure and effect of roughness is significantly noticeable. The same slopes of capillary penetration at different holes shows that the pressure gradient which is the same in all holes is the main driving force at this regime of penetration.

At the height of impact of 3mm, penetration into centre hole, first right hole (R-1), first left hole (L-1) has two specific regimes of inertia and capillary. No pause of penetration has been notices in this height of impact. In second right and left holes (R-2 and L-2) due to small energy of impact transferred into them, inertia driven penetration is extremely insignificant.

For the 3mm impact height, penetration into the centre hole, first right hole (R-1), first left hole (L-1) has two specific regimes of inertia and capillary. There is no pause in the penetration. The inertia driven penetration in the second right and left holes (R-2 and L-2) is extremely small, since the impact energy transferred to them is small. At the 5mm impact height, the impact energy is large, and the penetration is clearly inertia driven even for L-2 hole. The droplet rebound results in a short penetration pause, followed by a steady capillary penetration.

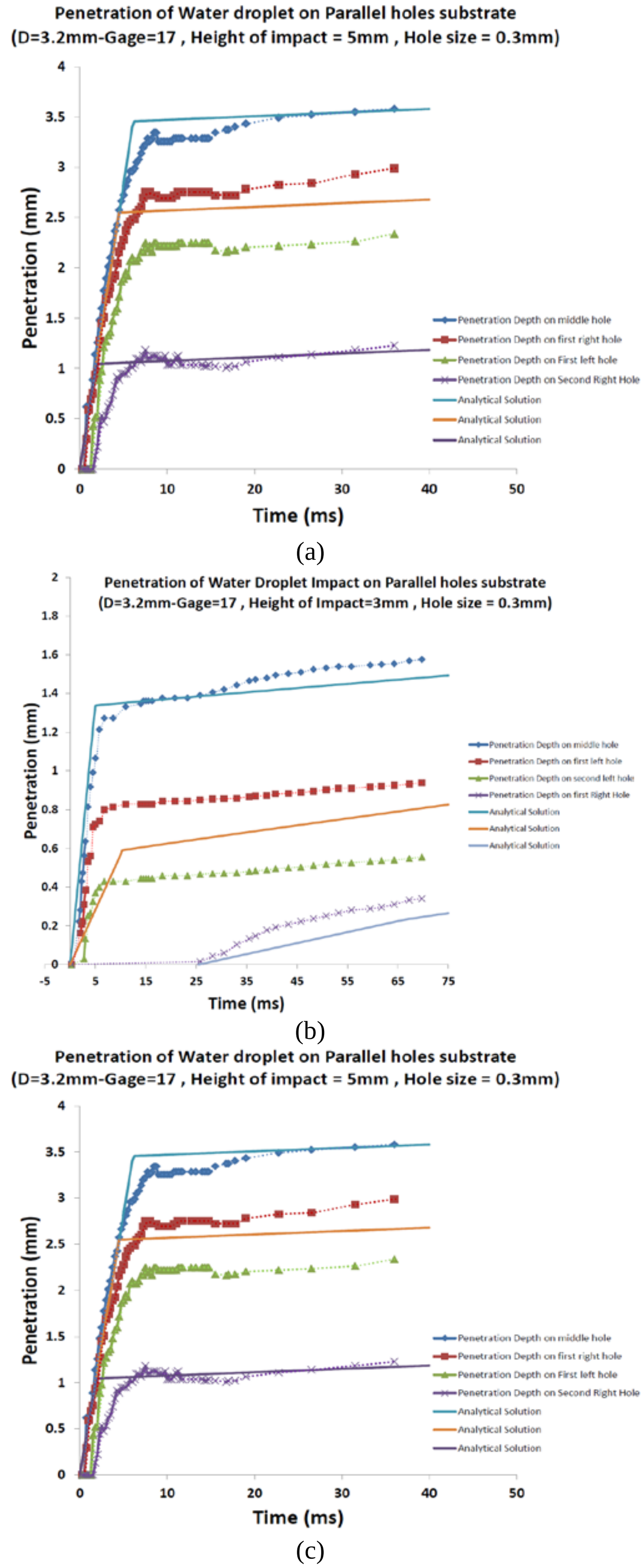

Figure 4 : Penetration of liquid droplet on line of parallel holes at height of impact of (a) 1mm (b) 3mm and (c) 5mm.

At the end of the inertia driven regime, the penetration for the centre hole is 0.4, 1.35 and 3.45 mm, for impact heights of 1, 3 and 5 mm, respectively. This measurement for R-1 holes are 0.25, 0.8, 2.6 mm, and for the L-1 holes are 0.22mm, 0.45mm, 2.2mm. At the end of capillary driven regime, the penetration for the centre hole for the three heights are 0.95, 1.6 and 3.5mm, respectively. These measurements show that 45%, 84% and 97% of penetration for the impact heights of 1, 3 and 5mm, respectively, occurs at the inertia driven regime. By dividing the penetration dynamics in these two categories, we can develop a simple model for the penetration of a impacted droplet into capillaries.

2.1 Inertia Driven Penetration

The pressure at the entrance of each hole pushed the liquid inside that hole. Assuming that all of the initial impact velocity is transformed into the dynamic pressure at the instance of impact, the pressure due to the impact is $\rho v_{imp}^2/2$, where v_{imp} is the impact velocity, and ρ is the fluid density. The pressure inside the droplet is $2\sigma/r_{drop}$ and that inside the capillary hole is $2\sigma Cos\theta/r_{hole}$, where σ is the coefficient of the surface tension, θ is the contact angle of the liquid and capillary wall, and r_{drop} and r_{hole} are droplet and hole radii, respectively. Therefore, a force balance for a fluid element penetrating into a hole can be written as:

$$\frac{1}{2}\rho(v_{imp})^2 = \frac{2\sigma\cos\theta}{r_{hole}} - \frac{2\sigma}{r_{drop}} \qquad (1)$$

Contact angle of water into the capillary hole during the liquid penetration is measured with a high speed camera, and it is found to be in the range of 80° and 100°. For this contact number, the first term on the right hand side of equation 1 can be neglected.

Since the droplet spreads radially along the surface of the substrate, the local impact velocity, v_{imp}, is different for each hole. In order to estimate the local liquid pressure as the droplet spreads over the substrate, the droplet impact process is assumed to be similar to the stagnation flow problems. The steady stagnation flow can be solved considering the following momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \upsilon[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}]$$
$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \upsilon[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}] \qquad (2)$$

Considering an axisymmetric flow with no slip boundary condition, and using stream function formulation, $u=-\psi_y/x$ and $v=-\psi_x/x$, where the subscripts represent derivatives. The stream function for this stagnation flow problem is written as $\psi=-Bx^2y$ and a similarity solution of the following form is found: $\psi=xF(\eta)(B\mu)^{1/2}$, where $\eta=y(B/y)^{1/2}$. By applying this stream function into the boundary conditions, the following nonlinear equation is found:

$$F''' + FF'' + 1 - F'^2 = 0 \qquad (3)$$

This equation is solved numerically to determine the pressure and velocity at the top of each hole, as shown in Figure 5 for a droplet impacted from 5mm height.

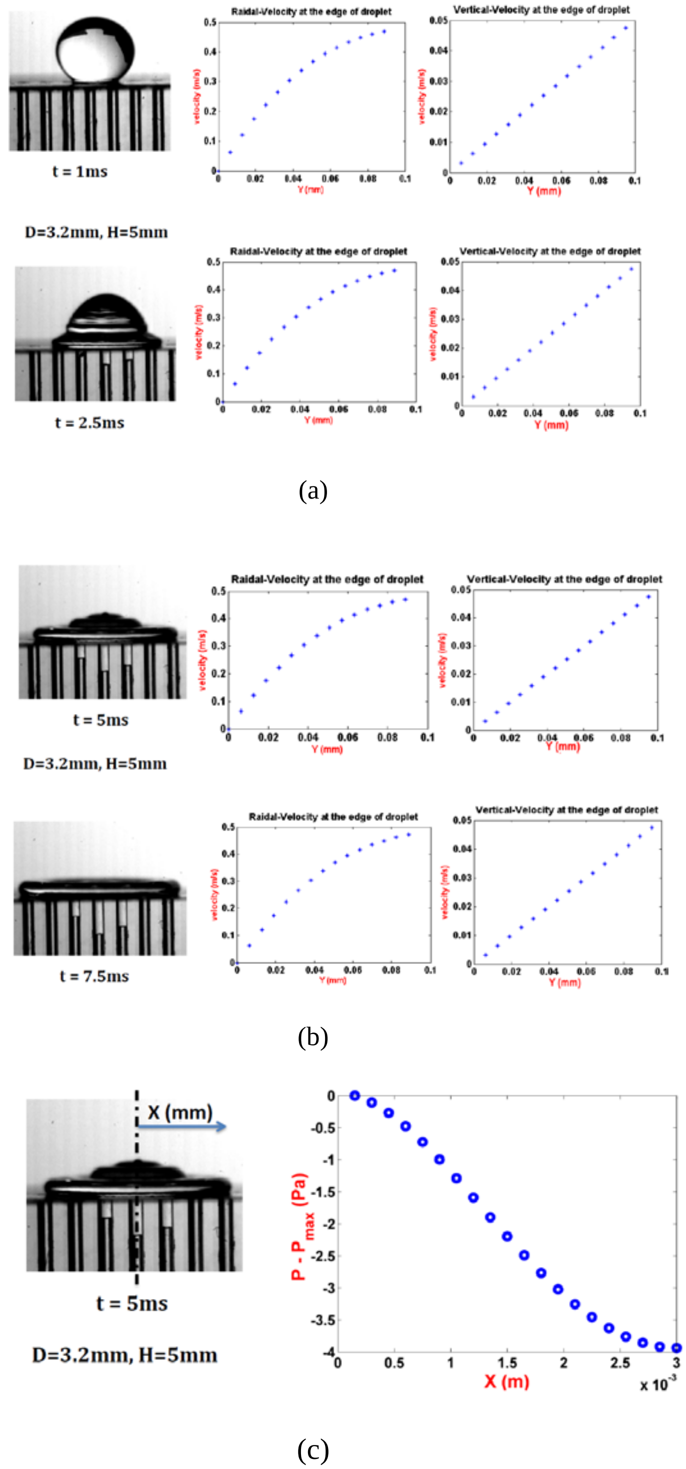

Figure 5: Analytical solution of pressure and velocity field inside the droplet (a) t=0 to t=2.5ms (b) t=5ms to t=7.5ms and (c) Pressure gradient.

The results show that the pressure gradient along the diameter of droplet is small, and therefore, it can be assumed to be constant. The maximum pressure difference at the top of the holes is 3mPa. Therefore, the observed time lag for the penetration between different holes is not due to the pressure difference between them, but due to the time it takes for the fluid to reach over each hole. The farther away the hole from the stagnation point, the later the penetration starts.

Once the pressure at the top of each hole is known, the penetration can be determined by $PA=\rho Ah\ d^2h/dt^2$. Solving this non-linear second order ODE gives us the penetration in terms of time for the inertia driven regime. The analytical solution for each case is plotted in Fig. 4 for different impact height. The results compare well with the experimental data points, validating the existence of the initial inertia driven regime.

2.2 Capillary Driven Penetration

As the penetration results showed in Figure 4, after inertia driven penetration, the liquid continues penetrating into the hole in a slow rate due to the capillary suction. Generally, the capillary driven action starts when the droplet has completed its spread and has reached a quasi-equilibrium shape on the top of the substrate. Lucas-Washburn equation [26,27] can be used to describe the capillary penetration into the holes:

$$\Delta P + \frac{2}{r_{hole}}\sigma_{LG}\cos\theta = \frac{8\mu x}{r_{hole}^{2}}\left(\frac{dx}{dt}\right) + \rho\left[x\frac{d^2x}{dt^2} + \left(\frac{dx}{dt}\right)^2\right] \quad (5)$$

Where ΔP is the external pressure imposed to liquid, $\sigma_{LG}\cos\theta / r_{hole}$ is the driving capillary force with σ_{LG} being the surface tension of liquid and, ρ is the density and μ is the viscosity of penetrated liquid. The terms on the right hand side of LWE are viscous resistance and the inertia. Inertia effects are usually significant only in early stages of penetration and large values of r_{hole} or significant small values of μ. Solving this equation gives us the penetration as a function of time:

$$x = \sqrt{\frac{\sigma_{LG} r_{hole}\cos\theta}{2\mu}t} \quad (9)$$

The analytical results are plotted in Fig. 4 along with the corresponding data points.

The only extra terms, which affects LWE, is the oscillation of droplet. In every rebound oscillation, negative velocities transfers negative inertia along the holes direction, which reduces the capillary driving force. This sinusoidal force damps after number of oscillation that is neglected in our capillary calculation. Penetration pause between inertia and capillary regimes is due to the significance of rebound and this negative pressure field.

2.3 Droplet Oscillation

As explained earlier in this study, droplet rebound produces a pause in penetration in the transition of inertia and capillary driven penetration regimes. This receding and rebounding behaviors cause height and diameter oscillation after the impact moment. These oscillations have been measured in the experiments. Droplet height oscillation in Figure 6 for capillary holes and no-holes substrate at height of impact of 1mm shows oscillation damping is stronger in the case of capillary holes substrate. Comparing the 3mm and 5mm heights shows faster damping as the impact velocity increases. Same behavior is observed for the droplet spreading.

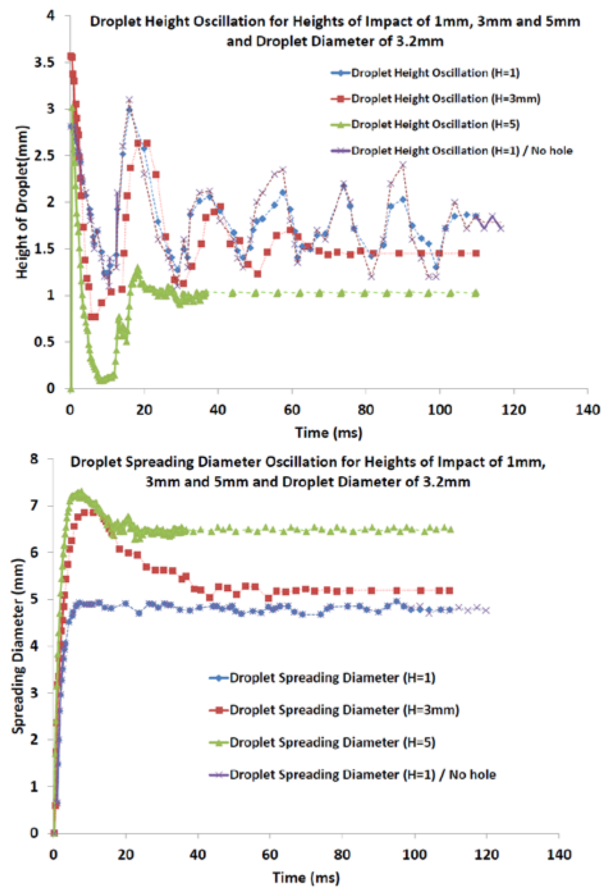

Figure 6: Oscillation of the droplet height and spreading diameter for impact heights of 1, 3 and 5mm.

CONCLUSIONS

We have studied the impact of a water droplet on a solid substrate having a line of parallel holes drilled through it. Two different regimes of penetration are identified: inertia and capillary driven regimes. The inertia driven penetration occurs within the time scale of the droplet spreading onto the surface of the substrate. Droplet rebound pauses the penetration process.

REFERENCES

[1] Bussmann M, Chandra S, Mostaghimi J. 2000. Modeling the splash of a droplet impacting a solid surface. Phys. Fluids 12:3121–32

[2] Chandra S, Avedisian CT. 1991. On the collision of a droplet with a solid surface. Proc. R. Soc. London Ser. A 432:13–41188

[3] Clanet C, Beguin C, Richard D, Quere D. 2004. Maximal deformation of an impacting drop. J. Fluid Mech. 517:199–208

[4] Cossali GE, Coghe A, Marengo M. 1997. The impact of a single drop on a wetted solid surface. Exp. Fluids 22:463–72

[5] Gentner F, Rioboo R, Baland JP, De Coninck J. 2004. Low inertia impact dynamics for nanodrops. Langmuir 20:4748–55

[6] Reznik SN, Yarin AL. 2002a. Spreading of a viscous drop due to gravity and capillarity on a horizontal or an inclined dry wall. Phys. Fluids 14:118–32

[7] Kim HY, Chun JH. 2001. The recoiling of liquid droplets upon collision with solid surfaces. Phys. Fluids 13:643–59

[8] Kim HY, Feng ZC, Chun JH. 2000. Instability of a liquid jet emerging from a droplet upon collision with a solid surface. Phys. Fluids 12:531–41

[9] Mehdi-Nejad V, Mostaghimi J, Chandra S. 2003. Air bubble entrapment under an impacting droplet. Phys. Fluids 15:173–83

[10] Roux DCD, Cooper-White JJ. 2004. Dynamics of water spreading on a glass surface. J. Colloid Interface Sci. 277:424–36

[11] Rozhkov A, Prunet-Foch B, Vignes-Adler M. 2004. Dynamics of a liquid lamella resulting from the impact of a water drop on a small target. Proc. R. Soc. London Ser. A 460:2681–704

[12] Sikalo S, Marengo M. Tropea C, Ganic EN. 2002. Analysis of impact of droplets on horizontal surfaces. Exp. Therm. Fluid Sci. 25:503–10

[13] Sikalo S, Wilhelm HD, Roisman IV, Jakirlic S, Tropea C. 2005. Dynamic contact angle of spreading droplets: experiments and simulations. Phys. Fluids 17:062103

[14] Starov VM, Kalinin VV, Chen JD. 1994. Spreading of liquid drops over dry surfaces. Adv. Colloid Interface Sci. 50:187–221

[15] J. Kettle, T. Lamminmaki and P. Gane, “A review of modified surfaces for high speed inkjet coating”, Surface and Coatings Technology, Vol. 204, pp. 2103-2109, 2009.

[16] Bussmann M, Mostaghimi J, Chandra S. 1999. On a three-dimensional volume tracking model of droplet impact. Phys. Fluids 11:1406–17

[17] Davidson MR. 2000. Boundary integral prediction of the spreading of an inviscid drop impacting on a solid surface. Chem. Eng. Sci. 55:1159–70

[18] Pasandideh-Fard M, Chandra S, Mostaghimi J. 2002. A three-dimensional model of droplet impact and solidification. Int. J. Heat Mass Trans. 45:2229–42

[19] Pasandideh-Fard M, Qiao YM, Chandra S, Mostaghimi J. 1996. Capillary effects during droplet impact on a solid surface. Phys. Fluids 8:650–59

[20] I. Pezron, G. Bourgain and D. Quere, “Imbibition of a fabric”, Journal of Colloid and Interface Science, Vol. 173, p.p. 319-327, 1995.

[21] N.R. Morrow, “Recovery of oil by spontaneous imbibition”, Current Opinion in Colloid and Interface Science, Vol. 6, pp. 321-337, 2001.

[22] U. Pasaogullari and C.Y. Wang, “Two-phase transport and the role of micro-porus layer in polymer electrolyte fuel cells”, Electrochimica Acta, Vol. 49, pp. 4359-4369, 2004.

[23] A. Delbos, E. Lorenceau and O. Pitois, “Forced impregnation of a capillary tube with drop impact”, Journal of Colloid and Interface Science, Vol. 341, pp. 171-177, 2010.

[24] S. Chandra and C.T. Avedisian, “Observations of droplet impingement on a ceramic porous surface”, International Journal of Heat and Mass Transfer, Vol. 35, pp. 2377-2388, 1992.

[25] P. Yue and Y. Renardy, “Spontaneous penetration of non-wetting drop into an exposed pore”, Physics of Fluids, Vol. 25, pp. 052104-1-19

[26] Ahmad Hamraoui and Tommy Nylander, “Analytical approach for the Lucas-Washburn equation”, Journal of Colloid and Interface Science 250, 415-421, 2002.

[27] A. Marmur, “Penetration of a small drop into a capillary”, Journal of Colloid and Interface Science, Vol. 122, pp. 209-219, 1988.