Drop impact close to a pore: experimental and numerical investigations

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Abstract

This study is devoted to experimental and numerical investigation of drop impact and its penetration into a porous target. We have discovered a new phenomena of jetting of a fast spreading lamella on a single pore. Moreover, flow of the lamella leads to the liquid entrainment into the pore initiating its imbibition. The flow resulting from drop impact onto a plate with a single drop is then simulated numerically. The mechanism of jet formation is described in detail.

Introduction

Drop impact onto a dry or wetted interface is one of the elements of various industrial applications and one of the lovely topics of many research groups [1]. The phenomena of drop impact onto a smooth dry substrate is already well understood. The evolution of drop diameter is determined by the Reynolds number, Weber number and by the wettability [2]. The evolution of the dimensionless height of the lamella at the very initial stage is universal. It almost doesn't depend on the impact parameters [3]. At the later stages the lamella height is influenced by the flow in the near-wall viscous boundary layer [4].

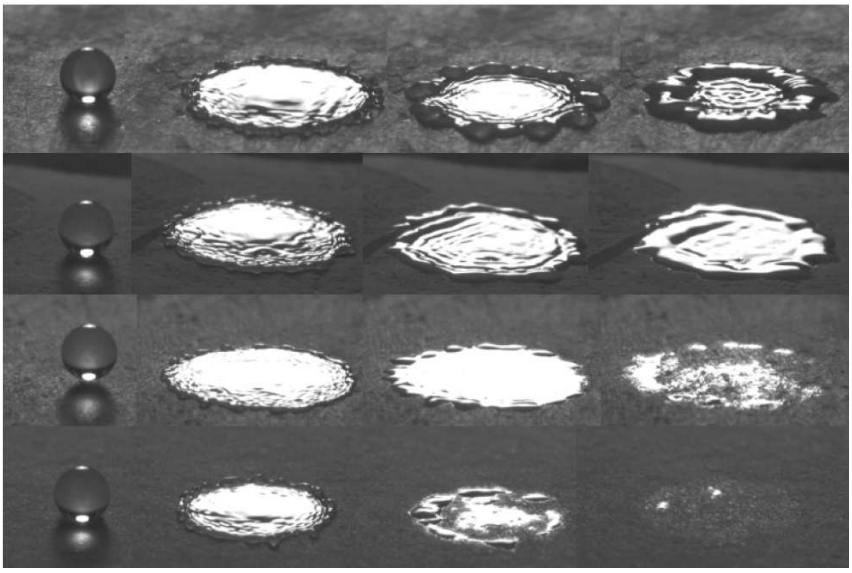

Figure 1. Drop impact on C1730III, CRS601II (porosity $\Phi = 59\%$, average pore diameter 3 .. 5 μm), CMS606II (porosity $\Phi = 63\%$, average pore diameter 15 μm) and CPS6011II (porosity $\Phi = 65\%$, average pore diameter 30 μm) (from top to bottom) [6]. Time between two succeeding images is 1.85 ms. Drop diameter $D = 2.35$ mm; impact velocity $V = 2.35$ m/s.

Much less is known about the mechanisms of drop impact onto a porous plates, which is relevant to ink-jet printing, needle-less injection, rain-soil interaction, *etc*. The effect of roughness on the splashing threshold of impacting drop has been demonstrated in [5]. It was shown however, that not only the mean amplitude of the roughness influences the magnitude of the threshold velocity but also the target material, probably through its wettability properties. This effect is not completely understood and no reliable model has been proposed for such phenomenon. Some new results demonstrating the effect of the surface morphology and porosity on the splashing threshold are presented in [6].

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Among the first studies devoted to drop penetration into porous plates is [7]. [8] focuses on investigation of impact of a small water drop onto a granular material initially covered by a thin layer of water film. Leads to the substrate erosion, water entrainment and pattern formation. Moreover, at some threshold of drop impact frequency the geometry loses its axisymmetricity and three-dimensional structures appear on the substrate.

Target porosity plays an important role in the study of drop impact onto a paper [9] - the topic associated with the ink-jet printing. An example of the direct numerical simulations of such phenomena can be found in [10], including the description of the drop spreading and penetration into the porous target.

Recently the research was extended by numerous experimental as well as numerical studies. The principal interest is addressed thereby on the procedures to the surface of the porous structure. In most of the studies random porous surfaces are used. Because of the small dimensions the mechanisms of liquid penetration into the pore cannot be investigated easily in detail. To obtain an better understanding of these procedures is the main goal of this investigation.

The main subject of the present experimental and numerical study is the investigation of a single drop impact onto a porous substrate. In order to get a better understanding of the physics behind the drop impact on porous media it is necessary to decompose the process into simple models. One of simplifying approaches is to model a porous media as a group of unconnected cylindrical vertical pores. Experiments on this setup have shown various interesting phenomena *e.g.* the development of a liquid-jet behind the pores. By further simplifying the model to a drop impact close to just one pore it is possible to investigate these phenomena in detail.

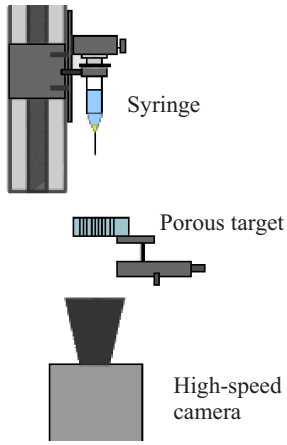

Figure 2. Experimental setup

Experiment

Experimental Setup

The experimental setup for investigation of single drop impact and its spreading on a porous plates is shown in figure 2. For the target a plexiglas pad with an array of not connected pores of 1 mm in diameter was used. The pictures were taken by a high-speed camera filming from below the plexiglas pad. Water drops of 2.5 mm in diameter were created using a drop generator installed at a variable height above the target. In the experiments the impact velocity, the distance between the impact axis and the holes, the size and the number of the holes have been varied.

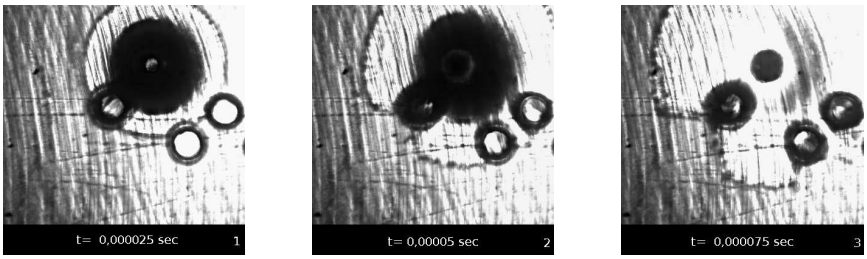

Figure 3. Time sequence of a drop spreading over three holes

Observations of drop spreading over holes

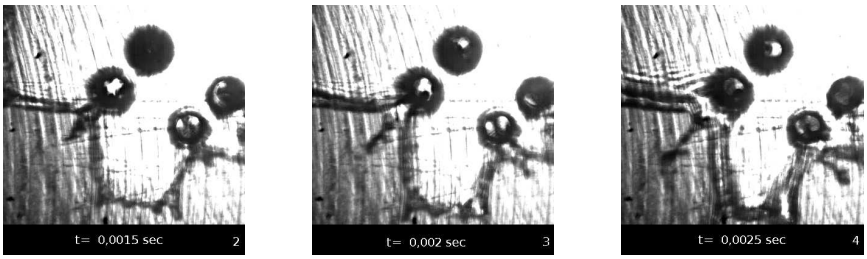

Figure 4. Drop spreading leading to the jet formation

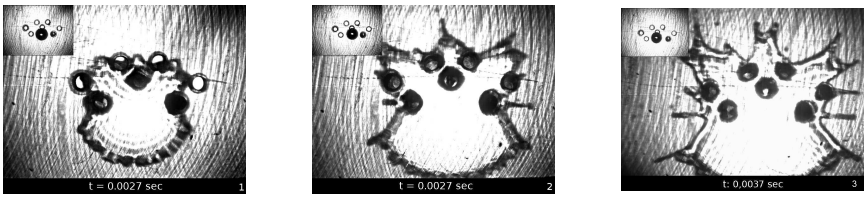

Figure 5. Maximum spreading state. The impact velocities are in the left image: $V = 1.4$ m/s, middle: $V = 3.1$ m/s, right: $V = 4.4$ m/s.

An exemplary picture sequence in figure 3 shows the moment when the drop flows over a pore. At the bottom of each image the time t after drop impact is recorded. In the left picture the drop just spreads straight over the pore. The shape of the lamella is almost radially symmetrical, its flow is almost not disturbed. At the instants shown in the pictures at the middle and at the right the hole starts to decelerate the lamella spreading and behaves as an obstacle. The front of the lamella strongly deforms and is no longer circular. With time this effect becomes more pronouncing, as seen in the right image. This phenomenon can be explained. Probably the liquid of the spreading lamella enters the hole and does not overflows it. Hole serves as a local sink. The shape of the front near the hole is defined by the local velocity in the lamella and be the relative velocity of the rim. The phenomenon is thus similar to the breakup of a free liquid sheet by an obstacle [11].

In figure 4 the case with higher impact velocity is shown. At the outside edge of the pores a narrow liquid jets starts to form. They are ejected in a radial direction with the center at the impact point. This case is rather interesting. Authors have never observed such phenomena before an have not found its description in the literature. The appearance of the jets cannot be immediately explained. On the other hand, it could be rather important to understand this phenomenon since it probably influences the splashing threshold and the process of drop penetration into a porous target. It should be noted that the appearance of the jets is not occasional. The jet are emerged systematically starting from a definite threshold velocity.

In figure 5 the maximum spreading for three different impact velocities is shown. The impact velocity in the left picture is $V = 1.4$ m/s. The lamella is disturbed in its propagation through surrounding pores, as it has already been described in figure 3. The jet formation does not take place. In the picture at the middle the impact with the velocity is $V = 3.1$ m/s is shown. The drop spreads to a larger diameter than in the case before. The effect that the liquid flow sticks behind the pore is intensified and in addition the jet formation arises. The recognizable dependence of the effects mentioned on the speed clarifies itself in picture three, where the impact velocity was $V = 4.4$ m/s. Not only the same jets appear from the hole but even the flow in the lamella between the holes is strongly deformed, breaks up and leads to the appearance of finger-like jets.

The experiments show that the behavior of a drop spreading over a pore, and generally on a porous material, is a more complex phenomenon than it might be assumed initially. To better understand the observed phenomena and in particular the mechanisms leading to the jets formation drop impact has been simulated numerical. These simulations are described in the next section.

Numerical method

Drop impacts have been numerically simulated using the interFoam solver of OpenFOAM v1.6. InterFoam models a free surface flow with a volume of fluid method based on a finite volume discretization.

The mesh used for the simulation (See figure 6) consists of 2.8 million hexahedral cells and includes two major features to improve the efficiency of the computation. The computational domain is split to one fourth by

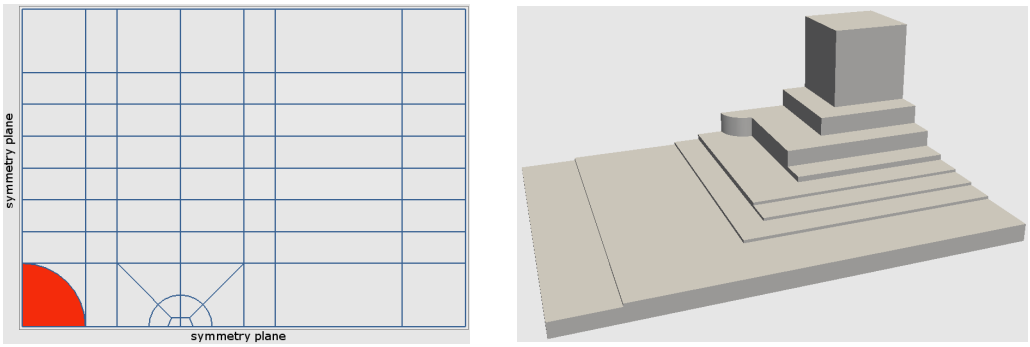

Figure 6. Left: 2D-View of the mesh structure. The drop impacts on the lower left corner; Right: Surface view of the mesh used for the simulations

introducing two symmetry planes. The mesh is built of stacked layers to ensure fine resolution of the flow in a liquid drop. The time discretization is varied dynamically during the simulation to ensure a maximum Courant-number of 0.5.

Only one hole has been simulated in this study. The drop spreading is assumed symmetric relative the plane which includes the impact and the hole axes. In order to reduce the computation cost only a half of the spreading drop is computed.

Results and Discussion

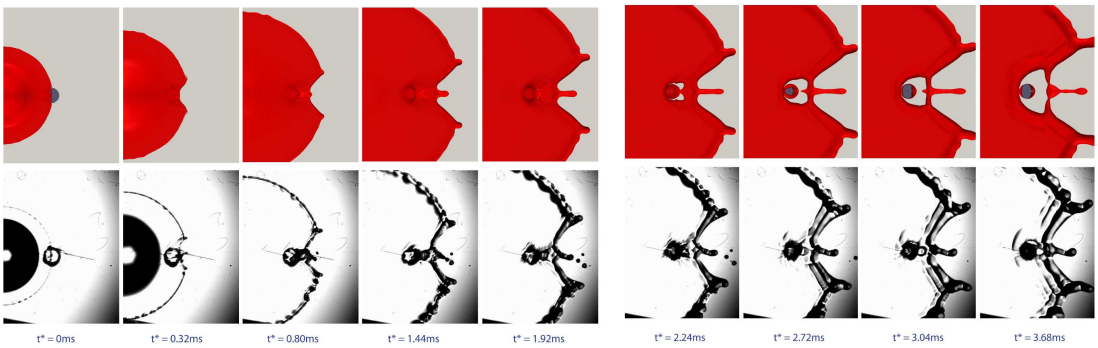

Figure 7. Comparison of the numerical simulations with experiments. Left: Drop spreading over a hole; Right: Drop dewetting near a hole

The results of the comparison of the numerical predictions of drop spreading over a single hole with the experimental data are shown in figure 7 during two stages: lamella spreading and receding. The agreement is rather good. Some overprediction of the dewetting on figure 7 is a known issue of the volume-of-fluid method. It is explained by the fact that extremely fine mesh is required to accurately describe film breakup. Such description of an extremely thin film is out of scope of the present study.

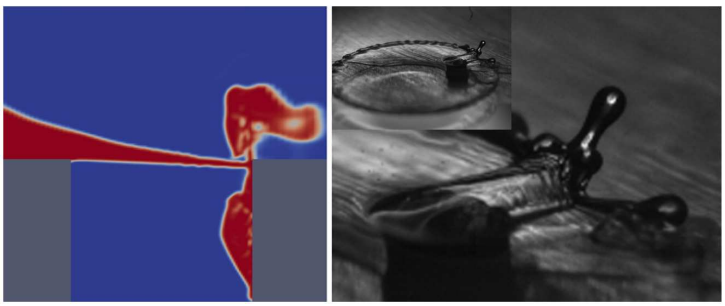

Figure 8. Splash of drop near a hole. Qualitative comparison of the numerical simulations with experiments

Our numerical simulations predict the emergence of the jets when the lamella flow over the hole. However, the upper view doesn't allow to explain the mechanism of their formation. Much more information is obtained by plotting the numerically predicted shape of the lamella in the cross-section made through a hole. An example of such shape is shown in figure 8. The flow in the lamella partially enters the hole and impacts the frontal part of the hole surface. This impact generates two main high-speed jets: one free uprising jet and the jet penetrating the porous media. The deviation of the spreading lamella and its acceleration towards the hole is probably caused by the very high shear stresses at the contact line released when the contact line passes over the hole. The uprising jet can be clearly seen in experiments (see the right image on figure 8).

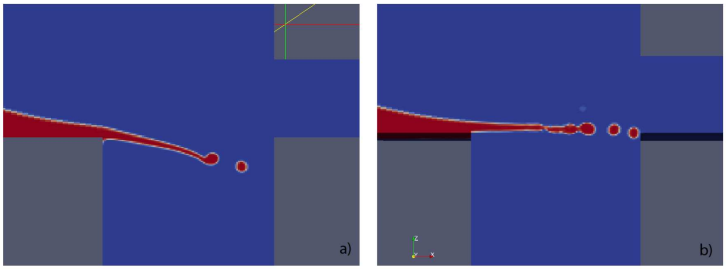

Figure 9. Effect of wettability on the lamella spreading over a hole; Side view on the cross-section. The contact angle is (a) 30° and (b) 110°.

It is interesting that despite the relatively high velocity of spreading (and thus to high Weber number) the wettability plays a significant role in the process of the lamella deviation over the hole. In figure 9 two cases are considered with different contact angles: $\theta = 30°$ and $\theta = 110°$. All other impact parameters are the same. The lamella deviation is much more pronounced in the case of wettable substrate. This deviation is enhanced by the capillary forces appearing at the walls of the hole.

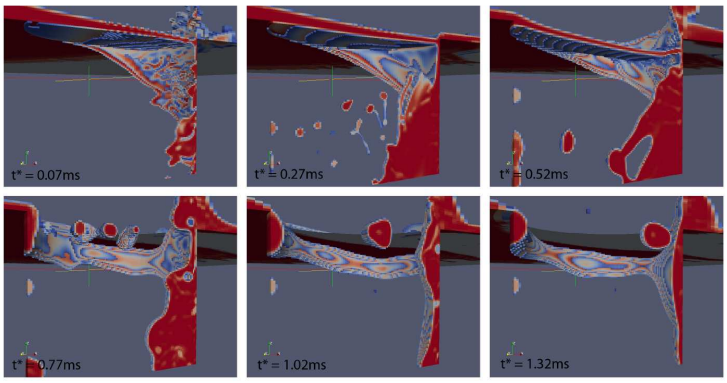

Figure 10. Liquid penetration into the pore. Impact velocity $V = 11$ m/s, drop diameter is 1.5 mm, distance to the pore 2.5 mm.

It should be noted that the flow over the hole is rather complicated and three dimensional, see the view on the on the symmetry plane on figure 10. Parts of the flow interacts with the walls of the hole and generate two streams along the walls in the polar direction. They collide at the opposite side of the wall. Such collision also contributes to the emergence of the jets.

It is obvious that inertia plays a major role governing the flow in the lamella and generation of the jets. In figure fig:veloc several cases of numerical simulations of drop impacts with different impact velocities are shown. While at relatively small impact velocities the lamella front is simply disturbed by the presence of the hole, at higher velocity it leads to the jet formation. In the case considered in figure 10 the threshold velocity is 7 m/s.

Conclusions

These experiments and numerical simulations show that the phenomena of drop impact onto a porous substrate is not so trivial as one could predict. It is reach of various phenomena. Some of them are investigated in this study experimentally and numerically. The mechanisms leading to the jet formation during lamella flow over a single

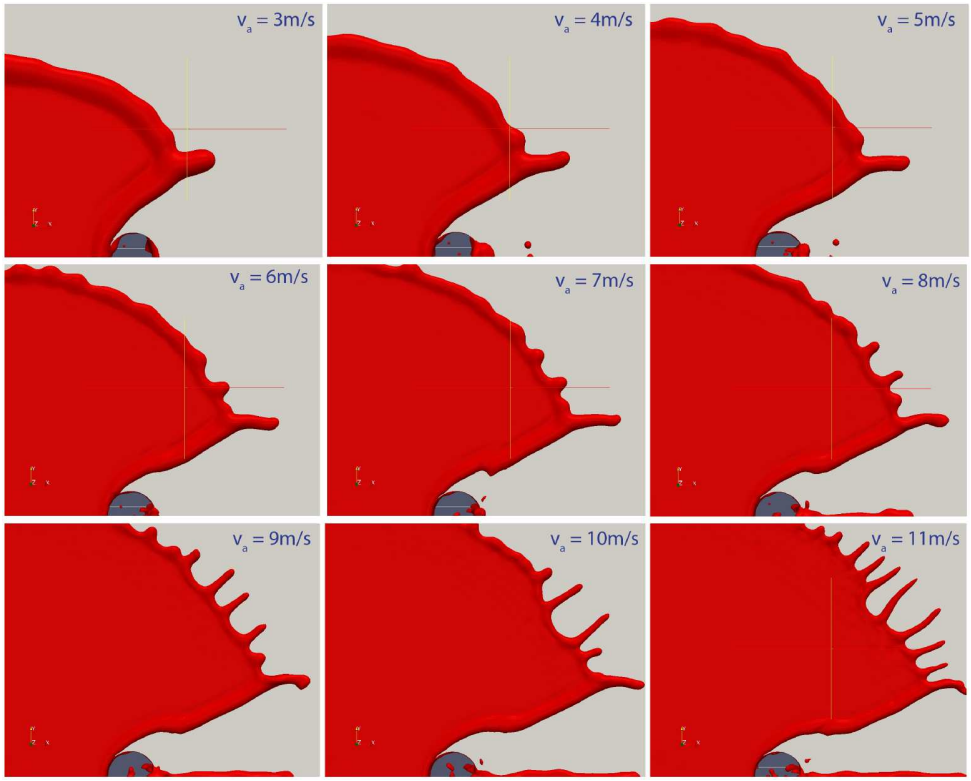

Figure 11. Maximum drop spreading at various impact velocities. Drop diameter is 1.5 mm, distance from the impact point to the pore center is 2.5 mm, pore diameter 1 mm.

hole are described in detail.

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