

Some Applications of Controlled Drop Deposition on Solid Surfaces

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Abstract: This paper reviews some industrial applications where a central role is played by the interaction between a surface and an impacting drop or spray. In particular, attention is focused on patents describing methods to optimize the application by controlling the drop deposition. This can be achieved, for instance, by using additives that change the fluid rheology, or by modifying artificially the state of the surface. The industrial applications considered here span across the whole range of engineering disciplines, from the distribution of agrochemicals to the fabrication of microlenses, and should be intended as examples of the potential as well as of the multidisciplinary of this topic.

Keywords: Sprays, drop deposition, solid surfaces, fluid rheology, agrochemicals, microlenses.

1. INTRODUCTION

The impact of liquid drops on solid surfaces is ubiquitous in a large number of applications, such as spray painting and cleaning, inkjet printing, pesticide distribution, spray cooling and firefighting devices, fuel atomization in internal combustion engines, and many others.

As it is well known, the behavior of a drop after collision with the surface is complex, and depends both on the physico-chemical characteristics of the drop and on those of the surface itself. Roughly speaking, according to the fluid properties, the impact velocity, and the surface roughness, a drop may either stick to the wall, or hit the wall and bounce off (partially or entirely), or break-down upon impact into smaller droplets, which is generally known as "splashing" [1], as shown schematically in Fig. (1).

In all cases the drop, during the first few milliseconds after making contact with the surface, is forced to spread, creating a disc-shaped liquid layer called lamella. Subsequently, the lamella retracts, and its behavior is essentially determined by the competition between inertial forces (depending on the drop kinetic energy) and capillary forces (depending on the surface tension). The relevant dimensionless numbers during the impact and the expansion phase are the Weber number, defined as:

$$We = \frac{\rho D_0 U^2}{\sigma} \quad (1)$$

and the Reynolds number:

$$Re = \frac{\rho D_0 U}{\eta} \quad (2)$$

where ρ is the fluid density, D_0 the drop equilibrium diameter, U the impact velocity, η the fluid viscosity, and σ its surface tension. These numbers express the ratios between

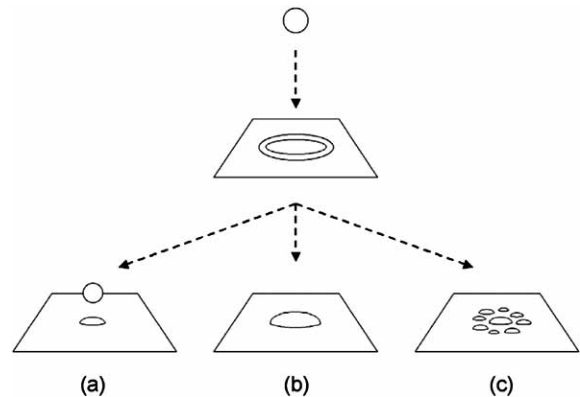


Fig. (1). Possible outcomes of drop impact on a solid surface after the initial spreading: (a) rebound, (b) deposition, and (c) splashing.

inertia and capillarity and between inertia and viscous dissipation, respectively. Sometimes, viscous dissipation is taken into account using the Ohnesorge number:

$$Oh = \frac{\eta}{\sqrt{\rho \sigma D_0}} = \frac{\sqrt{We}}{Re} \quad (3)$$

On the other hand, during the retraction phase the competition between viscous dissipation and capillarity, expressed by the capillary number, where the impact velocity is replaced by the retraction velocity of the lamella, U_R :

$$Ca = \frac{U_R \eta}{\sigma} \quad (4)$$

If the initial kinetic energy exceeds a threshold value (which is greatly lowered by surface roughness), drop splashing will occur, as shown in Fig. (1c): Capillary forces are insufficient to maintain the integrity of the drop, which disintegrates into smaller satellite droplets. A detailed study of this phenomenon [2] reveals that drop splashing can be further sorted into three main types. In particular, when one observes satellite droplets jetting out of the lamella from its

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outermost perimeter we have the so-called corona splashing; but drop break-up can also occur during the lamella retraction, which is the case of receding break-up. Finally, under some circumstances very small droplets can be observed immediately upon the drop impact (prompt splash).

On the other hand, if the drop is allowed to retract under the action of capillary forces, which tend to minimize the contact with the surface, the retraction can be so violent that the drop bounces off the surface, at least partially Fig. (1a). Drop rebound represents a major drawback in several practical applications of impinging sprays. In fact, the liquid fraction reflected off the wall is often wasted, which implies on one hand additional costs, and on the other hand environmental pollution, especially if the liquid contains toxic substances.

The general picture of drop impact on hot walls is even more complicated, especially when the wall temperature exceeds the saturation temperature of the liquid, because phase transition phenomena must be taken into account. For example, the process of breakup can be enhanced by boiling initiated at the contact points between the liquid and the hot wall. Therefore, the critical Weber number at which splashing begins is expected to be lower than in the case of cold wall.

A qualitative map of drop impact regimes as a function of the Weber number and the wall temperature [3] is presented in Fig. (2). When the wall temperature grows above the saturation temperature of the liquid, the onset of nucleate boiling occurs, with vapour bubbles migrating from the wall to the free surface of the liquid.

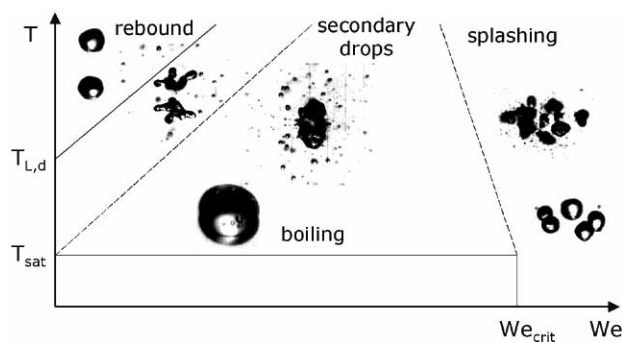


Fig. (2). Qualitative map of drop impact regimes on surfaces heated above the saturation temperature of the liquid.

If the Weber number grows beyond a critical threshold, the drop kinetic energy becomes too large, so that the combined effects of capillary forces and viscous dissipation are no longer sufficient to avoid splashing, and the drop loses its continuity. As temperature grows, more thermal energy is supplied to the liquid: as a consequence, one expects splashing occurs at a smaller critical value of the Weber number.

For intermediate values of the Weber number and of the wall temperature, secondary droplets bursting from the free surface can be observed [4, 5]. This phenomenon, which is sometimes called drop miniaturization, is due to the synergetic action of heating, convective currents, and fast-

rising vapor bubbles, resulting into local peaks of the dynamic pressure of the liquid near the free surface.

For high wall temperatures and low Weber numbers, reflection of drops off the wall occurs, due to the formation of a continuous vapour layer between the liquid and the solid surface, which is known as Leidenfrost phenomenon [6, 7]. Although this phenomenon looks quite similar to drop bouncing on homothermal surfaces, the vapour film elasticity has been shown to play a fundamental role in the mechanism of drop reflection from hot walls [3]. Thus, a dynamic Leidenfrost temperature can be defined as the smallest temperature for which the drop bounces off the wall without breaking-up or scattering secondary droplets. Its value has been shown to increase with the Weber number [8].

This paper reviews some patents describing various applications involving the interaction between liquid drops and a solid substrate, ranging from the formulation of phytosanitary products to optical communications. In all cases, the drop-surface interaction has been optimized in order to achieve the best overall performance of the process. Beyond their practical relevance, some of these inventions offer interesting opportunities for research and further developments.

2. DISTRIBUTION OF AGROCHEMICALS

An important application where the impact of drops on a solid surface plays an essential role is the distribution of agrochemicals and phytosanitary products. These are generally distributed as aqueous solutions which are sprayed on plants using various types of pumps; for larger cultivation surfaces, helicopters or small airplanes are often used. Thus, in order to maximize the effectiveness of the plant treatment, after the impact and the initial spreading drops should stick to the surface, as shown in Fig. (1b), avoiding both rebound and splashing. In fact, if a fraction of the liquid initially sprayed does not stay on the target plant but falls on the ground, it causes both a less efficient treatment and soil pollution, with an obvious increase of the cost.

Unfortunately, plant leaves are coated with a layer of waxy substances that help preventing the colonization of bacterial pathogens on the leaf surface. Such layer makes the leaf surface hydro-repellant (or hydrophobic), which makes drop deposition more difficult and favors drop bouncing Fig. (1a) and splashing Fig. (1c) depending on the impact velocity. Therefore, this is an example where methods to control drop impact are desirable. A second problem which occurs when agrochemicals are distributed from helicopters or airplanes is the spray drift caused by atmospheric currents: in this case, the spray cloud may be directed away from the target, especially if the diameter of droplets is small [9].

The invention reported in Patent WO0008926 [10] allows a significant mitigation of these problems, achieved by adding very small amounts (between 0.05 and 3 g/l) of flexible polymers to the formulation of phytosanitary products. Because of the aqueous formulation of pesticides, polymers of interest are water-soluble polymers with molecular mass between $5 \cdot 10^4$ and $5 \cdot 10^6$ g/mol, (in general, for a same type of polymer better results are achieved for higher molecular weights). Specific examples given are:

1. Polyhydroxylated polymers or co-polymers chosen among polysaccharides of vegetal, animal or bacterial origin, polyvinyl alcohol, polyphenolic alcohols and derived compounds;
2. Glycol-derived polyalkylenes, such as polyethylene oxide (or polyethylene glycol), polypropylene oxide, and their mixtures;
3. Polymers of vegetal origin, such as the byproducts from the production of wood pulp (lignosulfonates);
4. Polymers obtained from at least one saturated or insaturated monomer, with one or more carboxylic groups, or an amino or nitrile group, or a heterocyclic group containing nitrogen, as well as copolymers obtained from them.

Of course, the sticking agent can be one of the substances mentioned above, or a mixture of components, eventually belonging to different groups. As for the preparation of the final product, the selected substance can be either pre-mixed or added at the moment of application.

Due to the very small concentration of such additives, the viscosity of the product does not increase significantly, and remains essentially limited to less than six times the viscosity of water. This is important because should the additive cause a strong increase of shear viscosity, the energy required for pumping the fluid through the dispensing system would also increase. As for the surface tension, only additives with surfactant characteristics will reduce it significantly with respect to the value of the formulation without additive.

An example of the results achieved using such substances as sticking agents is reported in Fig. (3), which compares two drops (one of pure water and one of an aqueous solution of polyethylene glycol with a concentration of 0.2 g/l), falling from the same height, during the first milliseconds after impacting on a waxy hydrophobic surface. The two sequences clearly show that while the drop of pure water, after the initial spreading on the surface, quickly retracts and

bounces off, a drop of the same size containing the polymer completely adheres to the surface.

Finding the physical mechanism of this phenomenon has been the objective of extensive investigations in the recent past [11-14]. In particular, it was observed that for drops containing polymer additives the retraction velocity of the lamella after maximum spreading is significantly smaller than in the case of drops not containing the additive. Thus, the energy accumulated on the lamella surface during the expansion stage is not converted efficiently into kinetic energy, which causes the absence of rebound. Fig. (4), shows the evolution of the drop diameter in the first milliseconds after impact, for the drops shown in Fig. (3). The slope of these curves corresponds to the radial velocity of the lamella, and is positive during the expansion and negative during retraction. While almost no difference can be observed between the two curves before their maximum, which means that the two drops expand at the same velocity, the retraction velocity is much smaller for the drop containing the additive.

It has been argued that such reduction of the retraction velocity may be due to the very high elongational viscosity exhibited by polymer solutions. Unlike the commonly used concept of shear viscosity, i.e. the ratio between the shear stress and the velocity of deformation (the velocity gradient in the direction perpendicular to the stress), the elongational viscosity measures the response of the fluid to an elongational flow, i.e. when the velocity gradient and the applied stress are in the same direction, as illustrated in Fig. (5). For a Newtonian, incompressible fluid, one can easily verify that the elongational viscosity is three times the shear viscosity. On the contrary, for a polymer solution the ratio η_e/η , also known as Trouton ratio, can be of the order of 10^3 - 10^4 [15].

The correlation between the elongational viscosity of a polymer solution and the retraction velocity reduction with respect to the pure solvent has been proven by extensive experimentations [14]. However, these are not sufficient to establish a cause-effect relationship between the elongational viscosity and the anti-rebound effect. In particular, it has

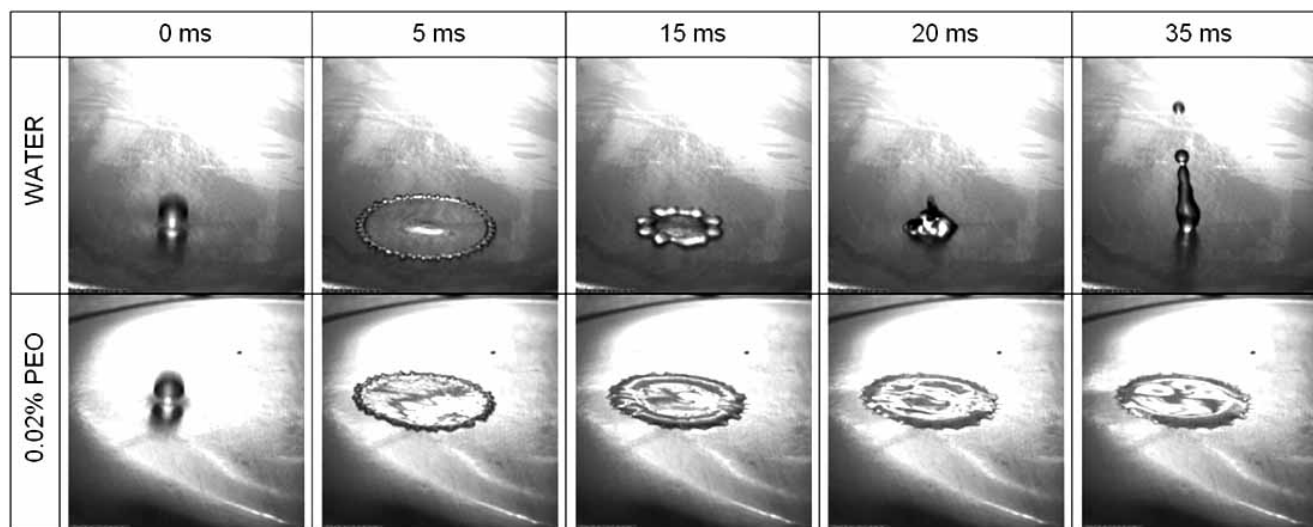


Fig. (3). Comparison between the impact of a water drop on a hydrophobic surface and that of a drop of a 200 p.p.m. solution of polyethylene glycol in water, with the same impact velocity.

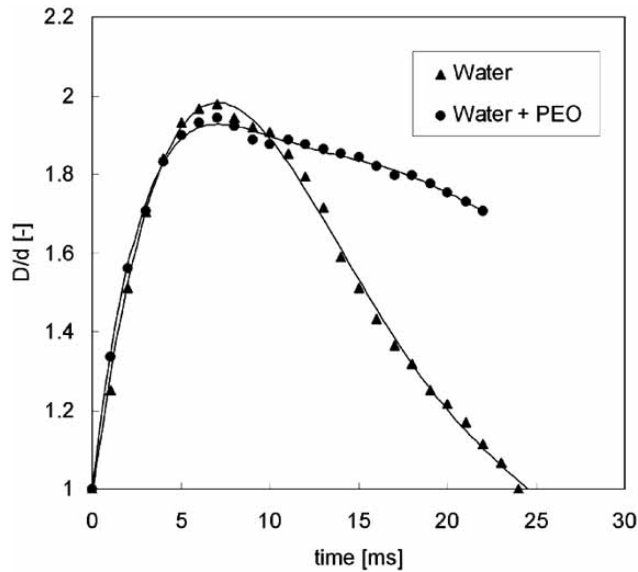


Fig. (4). Evolution of the drop diameter in the first milliseconds after impact.

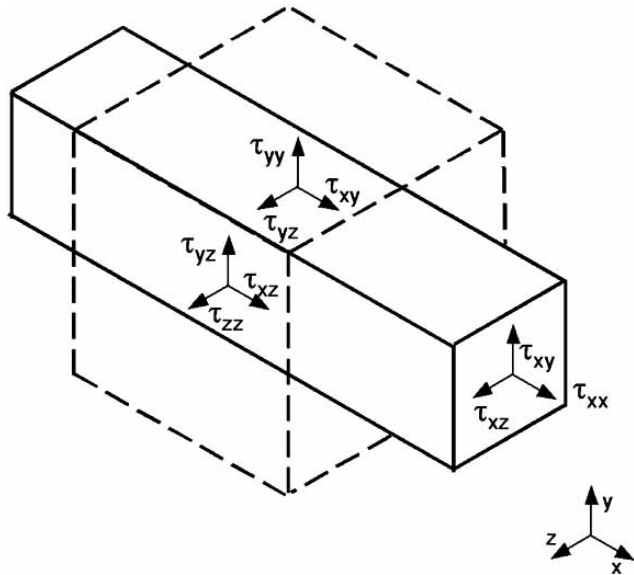


Fig. (5). Response of the fluid to an elongational flow, i.e. when the velocity gradient and the applied stress are in the same direction.

been recently observed that when wetting can be neglected completely, polymer additives do not prevent drop bouncing, and may even enhance it under some experimental conditions [16]. Therefore, the influence of some other parameters, such as the dynamic contact angle, might have been overlooked.

The benefits of polymer additives on the distribution of agrochemicals, however, are not limited to the anti-rebound effect described in Patent WO0008926 [10]. For example, it has been shown that these additives reduce the tendency of liquid drops with high kinetic energy to break down into smaller droplets, which otherwise may be scattered far away from the target surface. In other words, they increase the critical Weber number for splashing [13].

In addition, they affect the drop generation process in spraying nozzles, resulting into drops of higher average diameter than fluids having the same surface tension but not containing the additive [12]. This is particularly important in the case of fluids distributed using aircraft-mounted devices, because bigger and heavier drops are obviously less sensitive to drift.

3. RESISTANCE TO WASH-OFF

A problem that arises when delivering a substance through a spray is that once drops are deposited on the target surface the substances dissolved in them must remain in contact with the surface for a certain time in order to be effective. Improving the retention of the sprayed products is obviously necessary when spraying agrochemical, but also in aerosol drug delivery, sprayed paints, and many others.

However, very often the substances added to spray solutions must be highly water soluble to accomplish their intended task. Thus, the dried deposits of these solutions can be easily rinsed off by water and the active ingredients are transported with them, for example, as rain water runs off the leaf and onto the ground. Like poor deposition, this can lead to loss of product and soil contamination. Hence, improving the resistance to wash-off of sprayed deposits represents an additional challenge in spray treatments.

The invention described in Patent WO0056147 [17] tackles this problem by using specific additives that combine together as the drop dries to form an insoluble gel. In particular, these additives consist of at least one polyhydroxyl/polycarboxyl polymer or copolymer, and at least one cross-linking agent comprising a metal selected among columns IVA, IB and IIIB of the periodic table. The additives concentration in the aqueous spray mixture, must be such that the viscosity of the anti-leaching agent is not more than 10 times the viscosity of the aqueous solution in polymer or copolymer without cross-linking agent, having the same concentration. Where the complexing agent is poorly soluble in water, it can be used in conjunction with surfactants.

The formation of a water insoluble gel can take place easily if along the polymer backbone one finds a high number of hydroxide groups (-OH), which a large number of chemical constituents can associate with and thus form complexes with these polymers. Well known examples are borate ions and titanium dioxides. These smaller molecules bind to the hydroxide groups of different polymer molecules and form an interlaced network, which may be loosely bound with reversible binding sites or tightly connected into an insoluble precipitate. Of course, the properties of the network depend on the chemical nature of the binding agent, and the relative amounts and overall concentration of the polymer and binding agent.

This phenomenon can be represented on the qualitative phase diagram sketched in Fig. (6), plotting the percentage of complexing agent versus the percentage of polymer in the drop solution. During spray application and drop deposition the mixture is dilute in both components, which corresponds to a point in the liquid phase of the diagram (point 1). Once deposited on the surface, the solvent gradually evaporates,

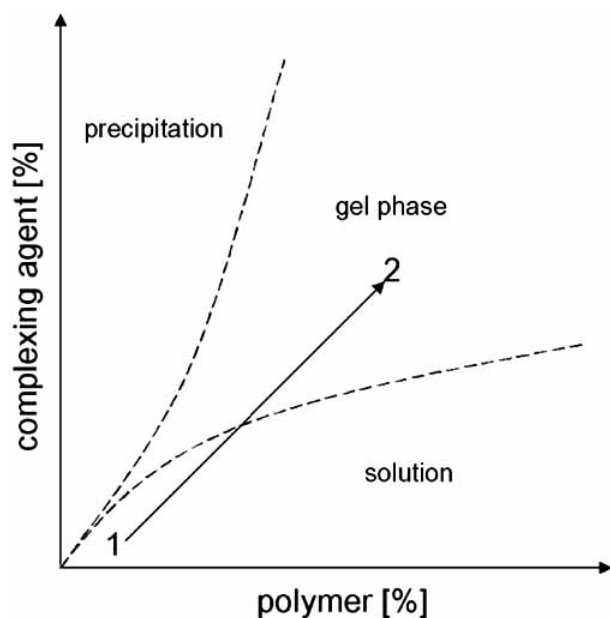


Fig. (6). Percentage of complexing agent versus the percentage of polymer in the drop solution.

and the concentration of both polymer and complexing agent in the solution increases until point 2, where the high concentration of both components produces an irreversible gel that becomes insoluble in water. The gel traps the active ingredients in its matrix and prevents them from being quickly rinsed off.

It must be observed that although this principle can be exploited in various application, Patent WO0056147 [17] makes explicit reference to the distribution of agrochemicals, and in some sense can be considered as an extension of Patent WO0008926 [10]. In fact, the choice of the polymer used is such that, when the mixture is in the liquid region of the phase diagram, it provides the solution with the required elongational viscosity to produce large drops that do not drift or bounce off plant leaves.

4. DROP-REPELLANT SURFACES

So far, the main focus of patents reviewed in the present article has been on technologies to prevent drop rebound after impact and enhance their adhesion. However, in other circumstances accumulation of liquid on a surface is unwanted, so that methods are needed to enhance drop bouncing, or avoid deposition. A typical application is the car windscreen, which ideally should be kept clear even during heavy rainfalls. Moreover, rain or other liquid drops often contain insects, bacteria or dirt particles, so that a surface able to reject such drops would also have self-cleaning properties.

The easiest way to reduce the tendency of drops to adhere to surfaces after impacting on them is to change the surface energy of the substrate, increasing its repellency towards the liquid. This goal can be achieved by applying on the substrate a film with suitable chemical composition: for example, in the case of water drops (which will be referred to for simplicity in the remainder of this section) fluorinated

alkylsilanes are well-known hydrophobic agents, whereas titanium oxide (TiO_2) has hydrophilic properties.

The degree of surface repellency towards a liquid can be characterized quantitatively by measuring the so-called contact angle between the free surface of a drop deposited on a given substrate and the substrate itself, which is determined by the thermodynamic equilibrium of the three phase gas, liquid and solid shown schematically in Fig. (7), and can be calculated from the well-known Young-Laplace equation:

$$\sigma_{SV} = \sigma_{SL} + \sigma_{LV} \cos \theta_c \quad (5)$$

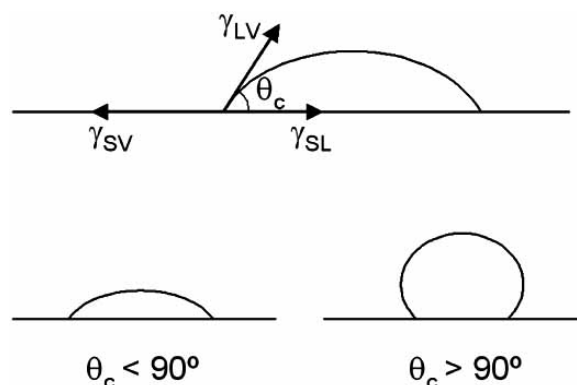


Fig. (7). The degree of surface repellency towards a liquid.

The liquid adhesion is stronger for small contact angles, and reduces in a continuous fashion as the contact angle increases. For very high contact angles ($> 90^\circ$), a drop can be moved easily on the surface, for example by aerodynamic forces or by its own weight if the surface is inclined. It must be noted that moving drops are no longer symmetric, and adhesion must be characterized in terms of the advancing and receding contact angles in the direction of movement, and of their difference (contact angle hysteresis) [18]. Roughly speaking, large advancing contact angles accompanied by small hysteresis are characteristic of hydrophobicity. However, if one goes beyond this simplified description of drop adhesion on solid surfaces and its characterization by means of contact angles will find several open questions, some of which are discussed in the most recent literature [19-23].

The invention described in Patent WO0064829 [24] consists in enhancing the hydrophobic or hydrophilic properties of a surface by means of a microscopic texture. In the particularly important case of hydrophobicity, these textured surfaces allow one to obtain very high water contact angles (of the order of 150° and more), and are usually called superhydrophobic surfaces.

The textures described in this patent consist of arrays of structures (not necessarily periodically spaced), which define a low-level and a high-level surface spaced apart by a distance not less than $1/10^{\text{th}}$ of the characteristic size of the structures forming the texture. The area of the high-level surface should be not more than 65% of the total area of the substrate, and the vertical surfaces connecting the two levels should be almost perpendicular to the substrate. The hydrophobic or hydrophilic character of the surface is obtained by

choosing suitable materials, and detailed examples are given for the two cases.

The structures forming the texture can have different geometries, including spikes, dimples and grooves. The patent also included a description of possible techniques to manufacture such structures (or their negative), which are sorted into four main types:

1. The texture is molded in a sol-gel applied on the surface, which is then hardened by evaporation;
2. The surface is coated with a compound that can be polymerized or cross-linked
3. The texture is created by a conventional lithographic or serigraphic process;
4. A textured adhesive film is applied on the substrate.

It must be remarked that due to the practical importance of superhydrophobic surfaces in industrial and biological applications, these and other manufacturing methods are well known and thoroughly described in the open literature [25].

5. DROPS ON HOT SURFACES

Many engineering systems involve the interaction of liquid drops with hot surfaces, with the most important applications being related to spray cooling and firefighting. In the recent years, the development of micro- and nano-technologies has increased the demand for miniaturized spray cooling systems which use only a limited amount of fluid.

In this context, US20016247525B1 [26] describes an interesting device to enhance the heat removal by inducing secondary atomization in a liquid drop deposited on a suitable surface vibrating at a frequency less than ultrasonic. In particular, vibration generates on the drop surface waves having a smaller length than the drop diameter, which become unstable and generate a spray of smaller droplets ejected and propelled away from the main drop [27]. If the spray is directed towards a hot surface, it allows a significant heat transfer improvement with respect to natural or forced convection.

Figure (8) shows a schematic description of a possible arrangement: a liquid droplet (a) is deposited on a surface (b) which is vibrated by one or more piezoelectric actuators (c), connected via wiring to a driver (d); the spray of secondary droplets (e) hits the hot wall (f). The vibrating surface can be, for example, a flexible membrane mounted on a rigid frame, while suitable piezoelectric actuators could be thin layers of piezo-ceramic materials (glued to the membrane itself), which expand and contract when a time-varying voltage with arbitrary amplitude and frequency is applied.

It must be remarked that this method to produce a spray is quite different from ultrasonic atomization, because the device operates at lower frequencies. As a consequence, the droplets are typically one order of magnitude larger than those produced by ultrasonic atomizers, and are ejected with a significantly higher velocity, of the order of some meters per second. If the amplitude of vibrations is sufficiently large, the entire volume of the drop can be converted into smaller droplets within a fraction of a second, much like a

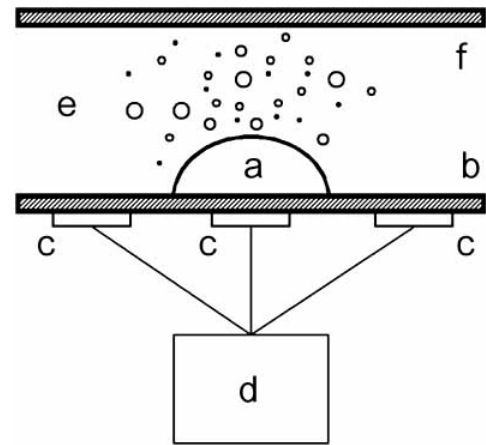


Fig. (8). A liquid droplet (a) is deposited on a surface (b) which is vibrated by one or more piezoelectric actuators (c), connected via wiring to a driver (d); the spray of secondary droplets (e) hits the hot wall (f).

bursting phenomenon. Finally, the power required by this atomizing process is very small, of the order of a fraction of a Watt, which allows the atomizing transducers to be extremely small and lightweight.

A limitation of this device is that it may not be suitable to work with any fluid. In particular, it has been shown that dilute solutions of flexible polymers (i.e., fluids containing additives of the same type described in Section 2 above) do not show secondary atomization even at very low concentrations [28, 29].

6. FABRICATION OF MICRO-LENSES

The rush to miniaturization of optical communication devices has rapidly increased the demand of microlenses (with diameters of the order of 100 microns) to be used in a variety of systems, ranging from solid state imaging elements to optical fiber connectors. Currently, micro-lenses are created by laser etching a suitable glass substrate, which ensures very high manufacturing precision and lens quality, but is extremely expensive in terms of both energy consumption and production time, hence the need of novel manufacturing techniques.

A simple and versatile method of fabricating polymer microlenses that can be easily integrated with optical devices [30] consists in dropping UV-curable epoxy resin onto optical devices by an ink-jet apparatus. When the epoxy resin droplet touches the surface, it takes the shape of a spherical cap Fig. (1b) with a contact angle depending on the properties of both the fluid and the substrate, as illustrated above. Because the resin is transparent to radiation in a given range of wavelengths, the curved surface of the drop can act as a lens.

To obtain a solid microlens, the liquid droplet is then irradiated with UV light, for a duration which is generally less than five minutes. Various microlenses having different geometrical diameters were successfully produced, by controlling the volume and viscosity of the polymer resin and their wettability to the substrate. Their uniformity in a

microlens array was measured to be within $\pm 1\%$ in diameter and $\pm 3 \mu\text{m}$ in pitch.

To prevent clogging of the nozzles used to create the microlens, the viscosity of the polymer liquid must be low, with typical values not greater than 50 mPa s. However, low-viscosity liquids spread easily on wettable surfaces, where the contact angle is very small, with the result that the drop diameter grows continuously after deposition. In particular, for Newtonian fluids the base diameter of a spreading drop varies according to Tanner's law [31]:

$$D \sim \left(\frac{\sigma}{\eta t} \right)^{1/10} \quad (6)$$

where t is time, σ is the surface tension, and η viscosity. Similar trends were obtained for the spreading of non-Newtonian fluids, such as the epoxy resins used in this microlens fabrication process [32, 33]. Therefore, controlling the drop size may be difficult as spreading continues during the UV-curing stage.

To solve this problem, one can control the surface energy of the substrate, for example by coating it with a thin liquid-repellant layer as suggested in Patent JP240911 [34]: Because these surfaces have higher contact angles, after deposition droplets do not spread as much as those deposited on wettable surfaces, resulting into microlenses of smaller diameter. The drawbacks of this solution are that the lens shape is strictly determined by the characteristics of the surface, limiting the flexibility of design; moreover, the adhesion of the lens on a liquid-repellant substrate is poor.

In order to reduce the drop maximum spreading after deposition without altering the surface wettability, Patent US2006012058 [35] introduces a technique where the drop is irradiated at least once between ejection from the dispensing nozzle and landing on the substrate. In fact, if the liquid used to form the microlens contains UV-curable polymers (preferably epoxy resins), exposure to UV radiation immediately after ejection from the nozzle initiates the hardening reaction, with the result that the viscosity of the liquid increases significantly at the moment of impact. Increasing the viscosity of the fluid creates a resistance to capillary forces [18], so that drop spreading on the substrate is limited. It should be noted that using this method, the fluid method the fluid viscosity inside the nozzle remains low, to ensure protection from clogging.

However, when implemented industrially this method revealed a severe drawback consisting in the fact that even if the fluid has a very high viscosity, the drop still shows a slow but continuous deformation after deposition on the substrate, driven by wetting and possibly by the residual elasticity of the UV-curable polymeric liquid used. Thus, after curing the lens has changed both its base diameter and its curvature, which makes extremely difficult controlling the lens shape (hence the focal distance) and ensuring production quality.

In Patent US2006012060 [36], this problem is fixed by implementing a manufacturing process that allows sufficient time between the drop deposition and the UV-cure to approach an equilibrium lens shape. However, in practice

this time can be of several minutes, which reduces considerably the process speed hence increases considerably the cost of production.

Finally, an interesting alternative microlens fabrication technique based on drop impact is described in Patent US2006262393 [37]. In this case, a drop of etchant liquid is deposited on the substrate (eventually coated with a layer of suitable material), creating a cavity. After removing the etchant liquid, a second drop of lens material is deposited in the cavity, and cured with UV radiation like in the procedures described above. Because the lens material fills the cavity, the lens diameter is perfectly controllable. If the substrate is coated with a liquid-repellant layer before etching, the drop material will not overflow, so that greater curvatures of the lens can be achieved.

7. CURRENT & FUTURE DEVELOPMENTS

Without being exhaustive, this review however shows that controlling the impact of liquid droplets on solid substrates can have a surprisingly large number of practical applications in fields that are completely different from one another. Thus, one can expect more and more to come in the future, the only limitation being apparently the creativity of inventors.

The most promising developments seem to be related to the use of additives that can change the fluid rheology. In particular, the potential applications of flexible polymers, which make the fluid viscoelastic without affecting significantly the other properties of the fluid, have been explored only partially, especially in the case of impact on hot surfaces [28].

Another property of non-Newtonian fluids that has a direct influence on the morphology of drop impact hence can be used to improve spray applications is the fluid yield stress [38], which can be defined as the stress threshold below which a fluid stops flowing and behaves like an elastic solid. This property could be useful, for instance, to improve manufacturing of microlenses: in fact, if the residual stress after deposition is smaller than the yield stress, the drop will keep its shape, without changing its base diameter before and during the UV-curing stage.

As for developments concerning the impact surface, current trends focus on the creation of active surface, which change their characteristics in response to an external action, such as the application of an electric field. Of particular interest is the fabrication of surfaces coated with polymer brushes [39], which can be switched between a coiled state, where they form a layer of uniform thickness, and a stretched state, where they take the form of spikes making the surface super-hydrophobic.

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