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Hydrodynamics and physics of soft objects/Hydrodynamique et physique des objets mous

Designing intelligent fluids for controlling spray applications

Mise au point de fluides intelligents pour le contrôle de l'application de solutions vaporisées

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Abstract

Recent advances in our understanding of 'complex fluids' have led to the development of new chemical additives in the agricultural industry, which provide more efficient products and a higher level of public and environmental protection. Here we present one example that deals with the improved application of herbicides and pesticides during the spray treatment of plants. Using judiciously chosen dilute polymer solutions, one can simultaneously improve the spray characteristics, droplet deposition, and product retention onto the targeted plant surface. Achieving these combined benefits, requires a delicate balance between fluid hydrodynamics and the molecular interactions that control the phase behaviour of the sprayed solutions. *To cite this article: V. Bergeron, C. R. Physique 4 (2003).*

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Résumé

Les récents progrès concernant la compréhension des « fluides complexes » ont permis le développement de nouveaux additifs chimiques utilisés dans l'industrie phyto-sanitaire qui ont abouti à des produits plus efficaces et à un haut niveau de protection environnementale et publique. Nous présentons ici un exemple concernant l'amélioration de l'application des herbicides et des pesticides durant leur vaporisation sur des plantes. En choisissant judicieusement des solutions diluées de polymères, il est possible d'améliorer simultanément les caractéristiques du jet, la déposition des gouttes, et la rétention du produit sur la surface de la plante cible. L'optimisation de ces paramètres demande de trouver un équilibre entre l'hydrodynamique et les interactions moléculaires qui contrôlent le comportement des solutions vaporisées. *Pour citer cet article : V. Bergeron, C. R. Physique 4 (2003).*

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Mots-clés : Viscosité élongationnelle ; Rebond de gouttes ; Herbicides ; Pesticides

1. Introduction

Whether painting, printing or simply cleaning surfaces, spraying a fluid onto them is an event we encounter daily. However, in many cases the processes involved are very complex, and a multitude of different factors need to be considered. One such example is the aerial spray treatment of plants. Here we are faced with a whole host of different problems at various stages

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of the process. Furthermore, our task is complicated by natural phenomena such as weather and the plant's age. Recently, new advances in our understanding of 'complex fluids' has lead to novel solutions that greatly improve the spray application of agricultural formulations. In this article we discuss the development of new polymer additives that enhance both, spray deposition and retention onto plant surfaces.

The first obstacle one encounters during the spray treatment of plants, occurs once a fluid leaves the tip of the spray nozzle; spray droplets must find their way to the right crop and plant targeted for treatment. This step is made difficult by the fact that wind and air currents can entrain the droplets and cause them to drift off course on their way to the plant surface. This phenomenon is known as *spray drift*, and it represents a major problem, as pesticides and herbicides in the formulation can be deposited in undesirable areas with serious consequences, such as damage to sensitive adjoining crops, water contamination and health risks for animals and people. The droplets most prone to spray drift are usually small in size, less than 200 μm in diameter. Hence, one might think that drift can be easily solved by increasing droplet sizes (i.e., make the drops large enough and they can not drift away); however, this remedy introduces another problem when these drops reach the plant surface.

Upon impact onto the plant surface aqueous drops have a tendency to *splash or bounce* off and land on the ground. This effect is due to the wax-like layer of a plant leaf, producing a non-wetting interface that repels water. A crucial attribute that helps to control the colonization of bacterial pathogens on the leaf surface. This layer changes its non-wetting character throughout the lifetime of the plant, making it truly a moving target in all senses of the word. As a result, plants often retain less than half of the applied spray. This is both inefficient and hazardous since crop treatment chemicals in the formulation will eventually contaminate the soil and water supplies.

Contrary to spray drift, large droplets are detrimental during impact with a leaf surface. Because of their higher kinetic energy, large drops provoke more energetic collisions with the surface, leading to splashing and disintegration of the drop as it lands. Hence we see that there is a certain antagonistic effect concerning droplet size characteristics; large drops help control spray drift but promote droplet rebound. In the past we have lived with drop sizes that compromise these two effects, but, recent more stringent toxicology regulations to minimise environmental and health problems have forced use to develop new solutions to this problem.

Finally, the last step concerning the spray treatment of plants, addresses retention and adhesion of the active molecules onto the surface. After a drop successfully lands and stays on the surface, it is often desirable for it not to be washed off during the next rain shower. This later effect is termed *washing resistance*. As the active chemicals in the spray formulation are designed to be compatible and easily dispersed in water to facilitate spray treatment, they often have a tendency to readily wash off in the rain. Preventing wash-off while maintaining aqueous dispersability of the product can be a very delicate balance.

In this article we will discuss each of these challenges separately, *spray drift, impact, and washing resistance*, and show how recent research on complex fluids has been used to solve these problems. Advances in our understanding of non-Newtonian properties of polymer solutions, together with interactions in multi-component formulations have helped make important innovations in this area. When all these elements are brought together, these formulations provide a wide range of performance benefits.

2. Drift control – controlling droplet formation

After the first 'North American Drift Conference' at Portland, Maine in 1984, the subject of drift control has received much attention. This is largely due to new regulations put into place in North America since that time. Moreover, the subject of drift control extends far beyond aerial spray applications and now concerns ground applications as well. Table 1 provides a list of typical values one can expect for the drift of different drop sizes exposed to a cross-wind of 5 kilometers per hour. Clearly, droplets below 200 μm can significantly drift off target. The primary technical solution to this problem is to produce sprays with relatively large droplets ($>200 \mu\text{m}$) and a narrow drop-size distribution. Two different approaches have been taken to achieve this goal; modification of the spray-nozzle design and/or modification of the rheological properties of the spray fluid. It is the latter that we will focus on in the present case.

Table 1
List of typical drift values for a range of different droplet sizes

Droplet diameter (μm)	Type of droplet	Time required to fall 2 meters	Lateral distance travelled in falling 2 m with a 5 kph wind
5	Fog	66 min	5 km
20	Very fine spray	4.2 min	1 km
100	Fine spray	10 sec	13 m
240	Medium spray	6 sec	8.5 m
400	Coarse spray	2 sec	2.6 m
1000	Fine rain	1 sec	1.4 m

The principles behind the break up of laminar capillary jets to create droplets have been studied for over one hundred years, the work commencing with the publication of the studies by Savart [1] and Rayleigh [2], who investigated the behaviour of Newtonian liquids. Savart’s research showed that: (i) breakup always occurs independent of the direction of gravity, the type of fluid, or the jet velocity and radius, and thus must be an intrinsic property of the fluid motion; (ii) the instability of the jet originates from tiny perturbations applied to the jet at the opening of the nozzle. As the concept of ‘surface tension’ was not widely recognized in Savart’s time, it was Lord Rayleigh who first developed a quantitative analyses of jet breakup. Rayleigh realized that surface tension has to work against inertia, which opposes fluid motion over long distances. By considering small sinusoidal disturbances along a fluid cylinder of radius r , Rayleigh found that there is an optimal wavelength ($\lambda_r \sim 9r$), at which perturbations grow fastest and which sets the characteristic size of drops. Accordingly, the time scale t_0 at which these perturbations grow and eventually break the jet is provided by a balance between the surface tension and inertia;

$$t_0 = \left(\frac{r^3 \rho}{\sigma} \right)^{1/2}, \tag{1}$$

where ρ is the drop density and σ , the surface tension of the fluid. More recently, an excellent review covering the nonlinear dynamics and breakup of fluid jets has been given by Eggers [3].

The reason for concentrating on the study of the laminar capillary jet, is that it is the simplest possible flow system that produces drops, and in many cases relevant to the more complicated spray-jet breakup. This is particularly the case during fan-jet breakup for agricultural sprays, as pictured in Fig. 1. Initially, the spray exists the nozzle as a two dimensional sheet of fluid. This sheet then breaks up into a series of cylindrical ribbons which eventually undergo the same type of breakup as laminar capillary jets. To control the final drop-size in this process, recent emphasis has been placed on the use of non-Newtonian fluids made from dilute polymer solutions. In such cases, the classical findings of Rayleigh can be greatly altered.

Perhaps one of the most extensive experimental studies conducted on jet breakup of dilute and semi-dilute polymer solutions was that of Goldin et al. [4]. Middleman also made significant contributions to our understanding of the stability of viscoelastic jets [5]. These studies revealed that not only can the average drop-size be altered as a result of dilute polymer additives, but also the drop-size distribution. More recently, Mun et al. [6] have showed that these effects are primarily due to the non-Newtonian elongational (or extensional) viscosity of the fluids.

The elongational viscosity, η_e , corresponds to the viscous dissipation encountered when stretching a fluid, opposed to the more common notion of shearing a fluid (e.g., rubbing molecules against one another) which gives rise to the shear viscosity, η_s , see Fig. 2. It is the shear viscosity that we most often refer to has the ‘viscosity’ of the solution. For Newtonian fluids the elongational viscosity is exactly three times the shear viscosity, while for non-Newtonian fluids the elongational viscosity can exceed the shear viscosity by several orders of magnitude:

Newtonian fluids: $\eta_e = 3\eta_s$,
 non-Newtonian fluids: $\eta_e = T\eta_s$,

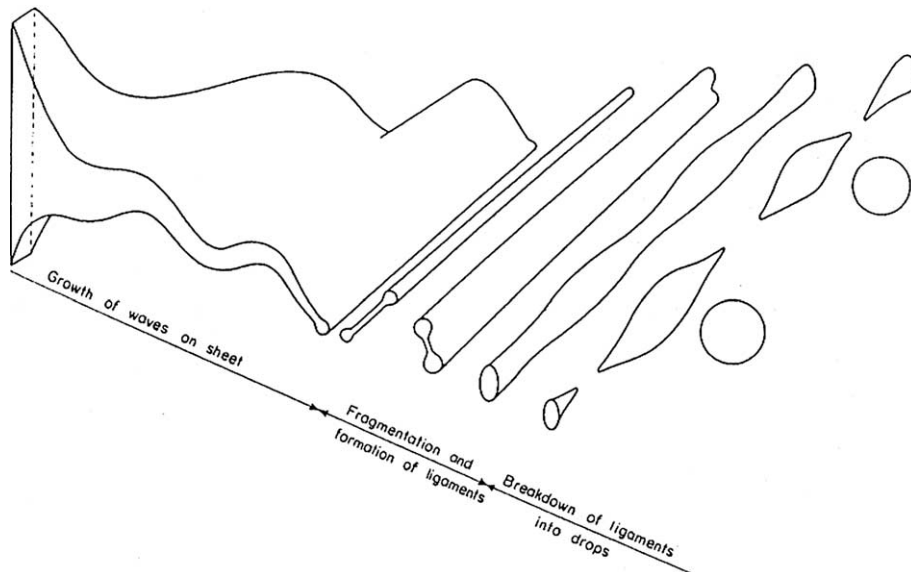


Fig. 1. Schematic illustration of the planar and cylindrical hydrodynamic instabilities that occur to produce drops from a fan-jet spray nozzle.

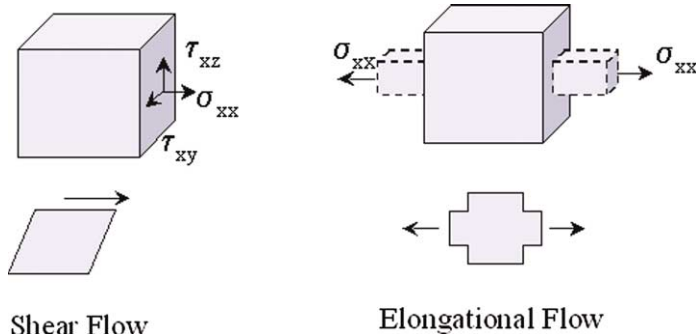


Fig. 2. Representation of the fluid movements that constitute the shear and elongational stress during flow. In each case the relation between the stress and rate of strain gives to viscous dissipation. This dissipation is characterised by the shear and elongational viscosity of the fluid depending upon the type of fluid movement.

where T is known as the Trouton ratio and can exceed 10^4 . Polymer additives that promote a high non-Newtonian elongational viscosity are those with a high molecular weight and flexible chemical backbone. The most well known polymers additives for aqueous solutions are polyacrylimide, PA, and polyethylene oxide, PEO.

In work of Mun et al., special dilute solutions known as Boger fluids [7] were used. These fluids are composed of low concentrations (~ 1 g/l) of high-molecular-weight flexible polymer dissolved in viscous, yet Newtonian, liquids (e.g., glycerol in water solutions). The high molecular weight of the polymer combined with the high viscosity of the solvent, boosts the relaxation time of the polymer, approaching that on the order of seconds. With such long relaxation times, strongly nonlinear effects are made much easier to study quantitatively. Doing so, Boger was able to show that the elongational viscosity can greatly retard the breakup of laminar jets in spray applications. Polymers in the solution stretch out as the fluid forms a filament, and the high elongational viscosity associated with this, stabilizes the perturbations that drive jet breakup. A schematic of this effect is presented in Fig. 3. As a result, the average drop size becomes larger and the drop-size distribution more narrow. Using dilute polymer solutions such as PA and PEO to produce large drops that do not drift off target, has lead to the development of so-called drift-control additives. These additives are able to reduce drift by as much as 80%.

3. Splashing and rebound – controlling drop impact

Although increasing the drop size is effective for solving the spray–drift problem, as mentioned earlier, it can have adverse side effects on droplet splashing and rebound off the plant surfaces upon impact. Like many seemingly simple physical phenomena, the process of a drop hitting a surface is much more complicated than it first appears. Not only does one have to consider aspects of the drop; its size, speed and nature of the fluid, but also the characteristics of the solid, such as its chemical composition and physical structure. For most plant surfaces it is a combination of repulsive chemical interactions and physical morphology of the leaf, that together create a surface capable of efficiently repelling the water and generating astonishing hydrophobic behavior [8]. In the most extreme cases these surfaces are referred to as super water-repellent surfaces.

The physical parameters that determine the outcome of an impacting drop are the inertial, viscous and capillary forces acting on the drop as it collides with the surface. The inertial forces result from the kinetic energy of the drop, and are determined by the drop's size, density and speed. Meanwhile, the fluid viscosity of the drop governs viscous dissipation, and the capillary force (i.e., surface tension) establishes the energy that is required to deform the drop. The dimensionless Reynolds, Re , and Weber, We , numbers are constructed from the physical parameters of the system, and are used to characterize drop impact by gauging the competition between the inertial forces, relative to the viscous dissipation and drop deformation. For drop impact these numbers are defined in the following way:

$$Re = \frac{\text{inertial}}{\text{viscous}} = \frac{Dv_i\rho}{\eta_s},$$

$$We = \frac{\text{inertial}}{\text{capillary}} = \frac{Dv_i^2\rho}{\sigma},$$

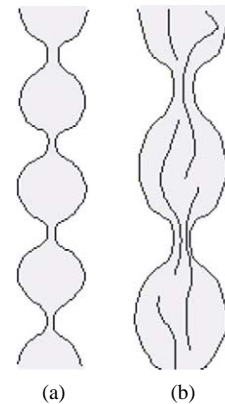


Fig. 3. Illustration of the break up of a laminar fluid jet of water (a) and a jet with a polymer additive. The high elongational viscosity provided by the polymer additive stabilizes the capillary instabilities, and leads to the formation of larger more regular sized drops.

where, D is the undeformed drop diameter, v_i , the drop impact velocity, σ , the fluid surface tension, ρ , the fluid density and η_s the solution viscosity.

When relatively large water drops, with a high kinetic energy, impact onto hydrophobic surfaces, two outcomes are generally observed; droplet *splashing* or *rebound* [9]. Fig. 4 provides an illustration of what is meant by these designations. The photographs accompanying the schematic diagrams in the figure correspond to images taken with a high speed camera operating at 500 frames per second. In both cases, during the first few milliseconds after the drop makes contact with the surface, the drop is forced to spread out in a radial direction along the surface in the form of a pancake. In general, *splashing*, case (a) in the figure, will occur when the drop impacts the surface with a very high kinetic energy (e.g., high drop-impact velocity and/or large drops). The threshold energy required for splashing to occur is greatly lowered by the surface roughness and splashing proceeds more readily on rough hydrophobic surfaces [9]. This effect is due to the limited contact that the drops have with the rough surface. During their radial expansion stage, the drops slide along the hydrophobic ridges of the surface leaving a cushion of air pockets between the drop and the surface. As a result, very little viscous dissipation occurs as the drop is forced to spread out over the surface. Consequently, nearly all of the kinetic energy of the drop is used to deform it upon impact. When the capillary forces are insufficient to maintain the integrity of the drop, it disintegrates into smaller satellite droplets jetting out along its outermost perimeter; the drop splashes off the surface as depicted in case (a) of Fig. 4.

Drops impacting onto smooth hydrophobic surfaces are not as explosive as those which collide with rough ones, however, problems can arise do to droplet rebound as depicted by case (b) in Fig. 4. In this case the drop first expands to a maximum diameter and then retracts under the action of capillary forces that act to minimize contact with the surface. This retraction can be sufficiently violent that the drop actually rebounds or bounces off the surface after impact. As with splashing, the outcome is the same; loss of product from the surface and inefficient deposition of the spray.

Intuition tells us that slow-moving, highly viscous drops – which have low Reynolds and Weber numbers – can dissipate all of their kinetic energy upon impact, leaving nothing to disintegrate or propel them off the surface. But high viscosity has its drawbacks, such fluids would be too difficult to pump and atomise through the spray nozzle. Therefore, simply increasing the fluid viscosity doesn't constitute a viable solution.

In almost all practical cases (particularly those concerning large drops for spray-drift control), we are faced with fast-moving drops composed of low-viscosity fluids. In this case, the impact and expansion of the drop are dominated by its inertial forces. The focus must then be placed on the final retraction stage of the process, as the drops try to minimize surface contact. The appropriate dimensionless number used to gauge this process, compares the capillary versus the viscous forces in the system, and is known as the, Capillary number, Ca ,

$$Ca = \frac{\text{capillary}}{\text{viscous}} = \frac{V_{\text{ret}}\sigma}{\eta_s},$$

where V_{ret} is the retraction speed of the outer rim of the drop as it shrinks after being forced into a pancake.

A convenient way to think about a recoiling drop after maximum expansion is to draw an analogy with a spring and dash-pot device. That is, imagine pulling a cylinder that is connected to a spring, through a cup of fluid until the maximum spring

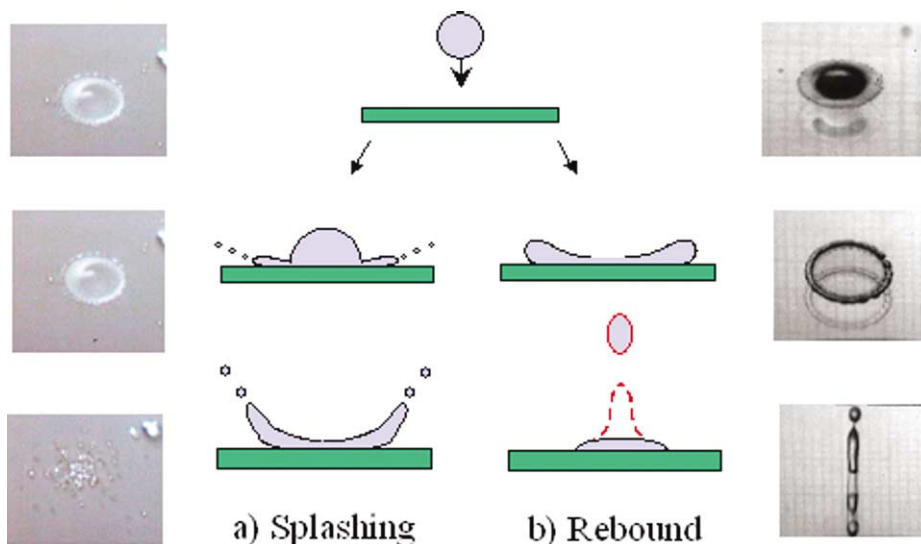


Fig. 4. Photographs and accompanying schematics of (a) a drop rebounding and (b) a drop splashing off a solid surface.

extension is reached – this would correspond to the maximum spread diameter of the drop. When the cylinder is released, strong springs tend to pull it out of the cup while a viscous fluid can prevent this from happening. Similarly, high surface-tension forces can propel a drop from the surface, while viscous dissipation within the fluid can hold it back, exhausting the energy stored by deforming the drop. This suggests two ways to prevent droplet rebound and keep it on the surface: we can either decrease the surface tension or increase the fluid viscosity. Recalling that the fluid viscosity must remain low for pumping and spraying, leads us to focus on lowering the surface tension. A lower capillary force enables the viscous forces to dissipate the kinetic energy of the system, even for relatively low viscosity fluids.

Decreasing the surface tension of aqueous solutions can be easily accomplished using surfactant molecules. In fact, many agricultural formulations already contain surfactants as dispersing agents for the active ingredients. Surfactants adsorb to the air–water interface by positioning their insoluble moieties out of solution into the adjoining air phase, while their water soluble constituents remain in solution. In doing so, the surface tension of water can be easily reduced by a factor of two. However, positioning of the surfactant molecule onto the newly created surface of an expanding water droplet takes a certain amount of time. If the molecule is too slow, it will not be effective in lowering the tension during the drop impact events. Therefore, not only must an added surfactants lower the tension, it must do so on the millisecond time–scale relevant to drop impact.

In 1997 Zhang and Basaran [10] and later Mourougou et al. [11] showed that indeed the so-called ‘dynamic surface tension’ (i.e., the surface tension of a newly formed interface as a function of time) is a property that can be used to prevent drop rebound. By measuring the dynamic surface tension and systematically comparing different types of surfactants, both teams found a clear correlation between fast lowering of the tension and non-rebounding drops. However, this method of preventing drop rebound is not particularly well suited for agricultural spray applications, because the same tension-lowering effect creates smaller droplets out of the spray nozzle that can easily drift off target. Drop rebound is not an issue if none of them make it to the surface. Furthermore, when we consider splashing of droplets, lowering the surface tension will further aggravate this problem – a lower surface tension will require less energy to disintegrate the drop upon impact. Hence a rapid decrease in the surface tension is not a solution towards better spray-droplet deposition onto plants. Low surface tensions can however be helpful for longer time events such as drop spreading after it has been deposited on the surface.

To resolve the dilemma between maintaining large drops that do not drift, but as a consequence are susceptible to rebound and splashing off the surface upon impact, we can once again call upon the non-Newtonian elongational viscosity of dilute polymer solutions. In addition to helping the problem of drift control as discussed earlier, the elongational viscosity can also be exploited for droplet rebound. Imagine the extreme deformations the fluid undergoes when it strikes a surface, we might expect that the high elongational viscosity of dilute polymer solutions could efficiently dissipate the energy during this process. An interesting perspective, as these same solutions can also have a very low shear viscosity, allowing them to be easily pumped and sprayed further upstream. In fact, the elongational viscosity of dilute polymer solutions is known to reduce the onset of turbulence during flow through the pipes, a phenomena referred to as ‘drag reduction’, which actually makes pumping easier.

Bergeron et al. [12] recently showed that dilute polymer solutions can indeed be used to prevent droplet rebound, by testing dilute solutions containing as little as 0.1 g/l of high molecular weight, $MW \sim 10^6$, polyethyleneoxide, PEO. Similar independent studies were also conducted by Crooks and Boger [13]. At these low concentrations, the polymer is scattered throughout the solution in small discrete clumps that have no noticeable effect on the solution properties (i.e., the shear viscosity and surface tension of the solution are not affected). However, stretching the fluid during drop expansion and retraction, unfolds and deforms the high molecular weight polymer molecules. This deformation drains energy out of the drop so it can no longer escape from the surface, see Fig. 5. Drops do not rebound because the inertial energy upon impact has been dissipated by the high elongational viscosity.

Additionally important is the fact that droplet splashing is also inhibited by the high elongational viscosity of such solutions. The final stages of droplet splashing involve a capillary instability of the outer rim of the expanding drop. This instability is similar to that encountered during the jet breakup when the fluid is sprayed out of the nozzle. Fluid accumulates at the leading edge of the drop, forming a rim that becomes unstable under the high inertial forces during a violent impact. Like with spray-jet breakup, the elongational viscosity helps to stabilise the capillary instabilities that occur at the leading edge of the drop and thus prevent it from disintegrating. Hence the drop stays intact and does not splash off the surface. These non-splashing drops also resist rebound for the same reasons outlined above.

The synergistic effects of increased spray-droplet size for drift control, combined with reduced droplet rebound and splashing, make dilute polymer solutions which have a high elongational viscosity, ideal candidates for improved agricultural sprays. This fact is borne out by the recent commercial release of products that use this technology. Considering the ecological and financial restrictions imposed on agricultural markets, one particular polymer that has led to great success in improving the deposition of sprayed herbicides and pesticides, is a polysaccharide known as guar gum. This polymer is extracted from the *Cyamopsis tetragonoloba taub* plant found in India and Pakistan, and is used widely as a food additive. This makes it excellent for sparying on plant surfaces. Guar gum also has a highly flexible molecular backbone and large molecular weight, which allow it to generate dilute solutions with a pronounced non-Newtonian elongational viscosity.

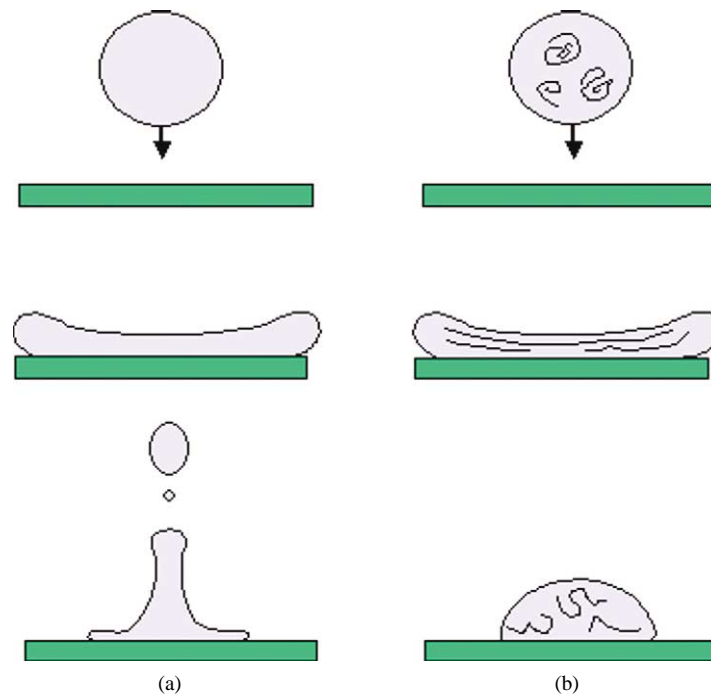


Fig. 5. Case (a) represents a typical water drop rebounding off the surface while in case (b) polymer additives in the drop provide a high elongational viscosity which dissipates the energy needed to propel the drop off the surface.

4. Washing resistance – drop retention

We have seen how dilute polymer solutions can improve drift control by increasing the drop size, and how these same solutions prevent drop rebound and splashing off leaf surfaces, but what can be done about retention of the sprayed products? The polymers and surfactants added to spray solutions must be highly water soluble to accomplish their intended task. This means however, that the dried deposits of these solutions can be easily rinsed off by water as these components are resolubilised. As a consequence the active ingredients (e.g., herbicides, pesticides, etc.) are transported with them as rain water runs off the leaf and onto the ground. Like poor deposition, this can lead to loss of product from the plant surface and soil contamination. This is particularly troublesome when it rains shortly after spray treatment of a crop, placing restrictions on when a crop can be treated and requiring reliable knowledge of the future weather conditions. Hence improving the resistance to wash-off of sprayed deposits represents an additional challenge in agricultural spray treatment.

In some respects the problem is similar to that of sprayed paints. Clearly a paint that runs off in the rain is not desirable. One of the principle ways to prevent this in a water-based paint is to add latex particles to the paint formulations. Latex, which is composed of synthetic, water-insoluble polymers, forms a continuous insoluble film upon drying of the paint which resists being washed off by water. Indeed certain latex derivatives (natural and synthetic) have been used in agricultural sprays to accomplish the same thing. However, these compounds provide no benefits to drift control or droplet rebound and splashing. Furthermore, the addition of highly water soluble polymers to improve spray drift and deposition, to latex containing solutions, interferes with the formation of the latex film upon drying. The water soluble polymers create defects in the film that allow it to be easily washed. Therefore, combining deposition additives with a latex retention additive does not provide combined benefits, and another strategy must be considered.

Starting with the fact that droplets containing a deposition control polymer like Guar gum, are positioned on the leaf surface, how can we transform them into water insoluble deposits upon drying? Fortunately, the chemistry of polysaccharides is well developed, and much is known in the paper industry about the complexation of such molecules to treat the surface of paper. Particularly advantageous is the high quantity of hydroxide groups ($-OH$) along the backbone of a polysaccharide, 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. Such networks can be loosely bound with reversible binding sites or tightly connected into an insoluble precipitate. 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. The task at hand is to develop a system that does not

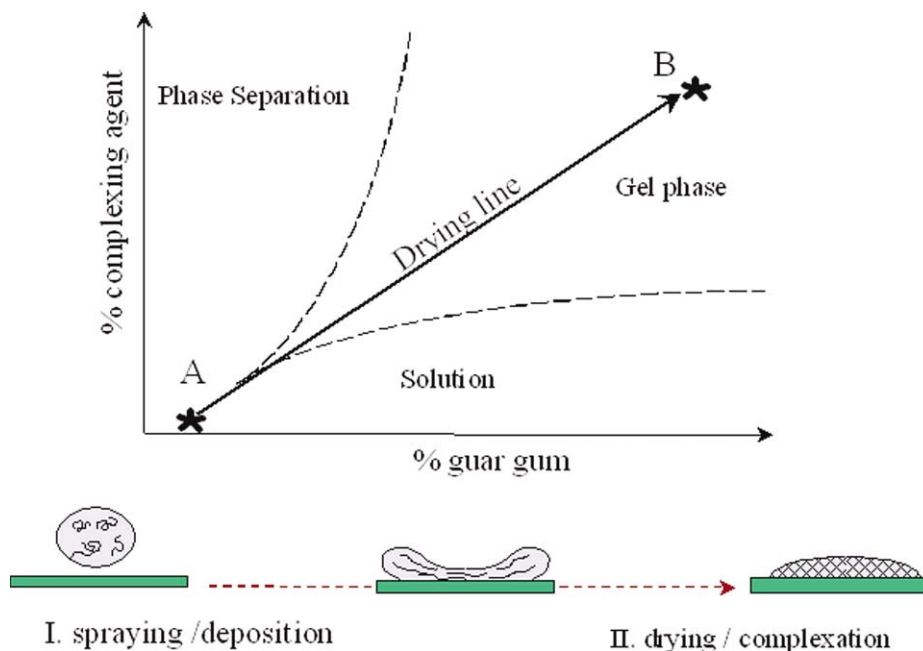


Fig. 6. Mixing a complexing agent to the dilute polymer solution can prevent wash-off of the product after drying. During the dilute stage (A) no chemical interaction between the agent and the polymer occurs but as the system dries and concentrates to point (B) an insoluble gel is formed.

bind when the drop solution is sprayed – thus leaving the polymer available for generating a high elongational viscosity for deposition control – followed by strong binding upon drying to create an insoluble matrix that resists wash-off. Schematically this is represented by a phase diagram for the polymer and complexing agent as sketched in Fig. 6. The diagram in the figure plots the percentage of complexing agent versus the percentage of polymer (e.g., guar gum) in the drop solution. During spray application and drop deposition the solution is dilute in both components, and we are in the fluid region of the phase diagram, indicated by the letter 'A'. In this region the polymer is highly soluble and not complexed, allowing it to provide the solution with the required elongational viscosity to produce large drops that do not drift or bounce off the leaves. Once deposited on the leaf surface, the solution evaporates, and we move along the line designated as the 'drying line' in the figure, until we reach point 'B'. At this stage the high concentration of both polymer and complexing agent 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.

5. Conclusion

We have showed that complex fluids can be used to solve complex problems. The spray application of agricultural chemicals, such as pesticides and herbicides, requires strict control of the processes involved to prevent health and environmental risks. The task is complicated by environmental conditions that can blow sprayed droplets into unwanted areas, or wash chemicals off the plants at undesired times. Using the non-Newtonian fluid properties of dilute polymer solutions, together with our knowledge of physical chemical interactions, new spray formulation have been developed that greatly reduces the risks present during the spray treatment of plants. The high elongational viscosity generated by flexible, high molecular weight, water-soluble polymers, stabilizes the capillary instabilities during spray breakup, and leads to large drops that do not drift off course. This same, non-Newtonian fluid property is used to prevent drop rebound and splashing as the spray drops impact the plant surface. Finally, as the solution evaporates of the leaf surface, chemical constitutes that form insoluble gels with the high molecular weight polymers, can be used help to fix the active ingredients to the leaf surface and prevent them from being easily washed away.

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