

Drop impact on a hot surface: effect of a polymer additive

V. Bertola

Abstract The impact of a drop on a hot surface is studied for Weber numbers between 20 and 220, and wall temperatures between 120 and 180°C. Drops of pure water are compared with drops of a dilute polyethylene oxide water solution (0.02% M). The additive is shown to inhibit drop splashing, the ejection of secondary droplets and mist formation. As previously observed, the polymer can also prevent drops from bouncing off a cold wall. This is no longer true if the wall is above the dynamic Leidenfrost temperature, which is lower for the polymer solution.

List of symbols

Ca	capillary number (-)
d	drop diameter (m)
D	lamella diameter (m)
k	coefficient in Eq. 3 (-)
g	gravity acceleration (m/s ²)
h	fall height (m)
m	drop mass (kg)
Oh	Ohnesorge number (-)
R^*	mean radius of curvature of the drop (m)
R_1, R_2	principal radii of curvature of the drop surface (m)
t	time (s)
T	temperature (°C)
u	perpendicular component of the impact velocity (m/s)
u_r	retraction velocity of the lamella (m/s)
v	velocity of secondary droplets (m/s)
w	velocity of the fluid inside the drop (m/s)
We	Weber number (-)
δ	secondary droplet diameter (m)
$\dot{\epsilon}$	rate of elongation (s ⁻¹)
η	viscosity (Pa s)
η_e	elongational viscosity (Pa s)
ρ	density (kg/m ³)

σ	surface tension (N/m)
τ	stress (Pa)

1 Introduction

The impact of a liquid drop on a solid surface is one of those everyday phenomena that attract the curiosity of many scientists because, despite its apparent simplicity, it conceals some nontrivial and challenging physics. The interest in understanding drop impact phenomena is also practical, because they play a major role in the optimization of several applications, such as spray applications, which are ubiquitous in industrial as well as in domestic processes, from painting or cleaning surfaces to injecting fuel into internal combustion engines. Therefore, the literature on drop impact is huge and still growing, especially since the introduction of high-speed imaging. Early works were carried out by Worthington (1876). Much later, in 1957, Edgerton was the first to apply the now famous stroboscopic photography technique to capture images of drops, as reported by Bergeron and Quéré (2001). Since then, much literature has been produced on this subject, both experimental and theoretical. Excellent and up-to-date reviews of drop impact phenomena and, more in general, of drop-surface interactions have been made by Frohn and Roth (2000) and by Rein (2003a).

The behaviour of a drop after collision with the surface is indeed very complex, and depends on the physico-chemical characteristics of the drop as well as on those of the surface itself. Accordingly, the drop may stick to the surface, bounce off, or splash and split into smaller droplets (Rein, 1993), 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 out in a radial direction, creating a disc-shaped liquid layer called *lamella*. Subsequently, its behaviour is essentially determined by the competition between inertial forces (depending on the drop kinetic energy) and capillary forces (depending on the surface tension). If the initial kinetic energy exceeds a threshold value (which is greatly lowered by surface roughness), drop splashing will occur: capillary forces are insufficient to maintain the integrity of the drop, which disintegrates into smaller satellite droplets jetting out of its outermost perimeter. 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

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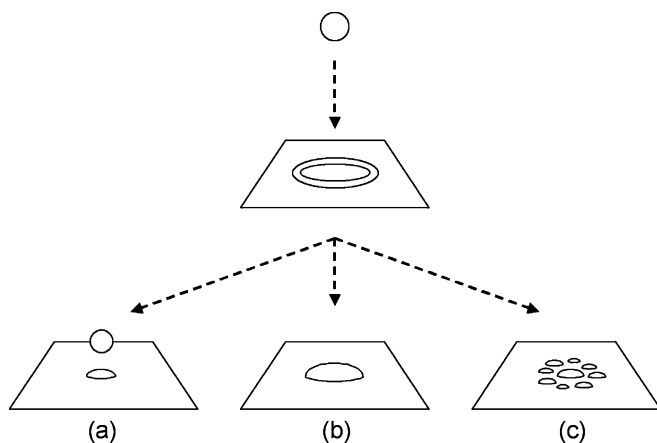


Fig. 1. Scenarios of drop impact on a dry surface; after the initial spreading of a circular lamella, eventually surrounded by a toroidal rim, the behaviour can be sorted into three main cases: a rebound (full or partial); b wetting; c splashing and break-up into smaller droplets

surface, the retraction can be so violent that the drop bounces off the surface.

To account for the competing action of inertial and capillary forces, drop dynamics is often described in terms of the Weber number ($We = \rho u^2 d / \sigma$). However, such description is not complete, because no mechanism for energy dissipation is included. For instance, one can change the rate of energy dissipation by changing the shear viscosity of the fluid and thus, highly viscous drops can dissipate all of their kinetic energy upon impact, leaving nothing to disintegrate or propel them off the surface. For this reason, drop splashing is sometimes characterized by the Ohnesorge number, which is defined as:

$$Oh = \sqrt{\frac{We}{Re^2}} = \frac{\eta}{\sqrt{\rho \sigma d}} \quad (1)$$

where $Re = \rho u d / \eta$ is the Reynolds number.

Of course, viscosity plays a very important role also during the retraction stage after maximum spreading (De Gennes 1985). In this case, the competition between capillary forces and viscous dissipation is expressed by the so-called capillary number ($Ca = u_r \sigma / \eta$), where the characteristic velocity is the retraction velocity of the lamella. A more refined model for spreading and receding of liquid drops on a dry surface has been recently proposed by Roisman et al. (2002), for Weber numbers that do not exceed the splashing limit.

This picture of drop dynamics becomes even more complex if the surface is heated above the saturation temperature of the liquid, because of the convective motions activated by the heat flux through the liquid and to the liquid–vapour phase transition. For example, the process of break-up 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.

In their classical paper Watchers and Westerling (1966) described the reflection of drops off a wall at high tem-

perature, as a result of the formation of a vapour layer between the lower surface of the drop and the hot wall. This phenomenon is analogous to film boiling (see e.g. Celata and Mariani 2003), and is called the “dynamic Leidenfrost phenomenon” after Gottfried et al. (1966). A dynamic Leidenfrost temperature can therefore be defined as the lowest temperature for which the vapour cushion causes bouncing of the whole drop (Rein 2003b). Yao and Cai (1988) showed that the dynamic Leidenfrost temperature increases with the Weber number.

Watchers and Westerling (1966) also observed that if the temperature is not too high, drop bouncing is accompanied by the formation of many secondary droplets that are ejected away from the main fluid volume, even if the Weber number is well below the splashing threshold. These droplets can be very small, so that they look like mist. This behaviour has also been described by Naber and Farrel (1993), and is similar to an analogous phenomenon occurring for sessile drops, consisting in the expulsion of minute droplets from the surface, which was called *drop miniaturization* by Inada and Yang (1993).

However, the goal of constructing a complete and detailed map of drop impact regimes as a function of temperature and of the Weber number has not been achieved so far, although remarkable works have been carried out in this direction (Bernardin et al. 1997).

Very often, drop impact may be affected by the presence of additives, which are used to give the fluid some specific properties (for instance, salt-containing additives are used to store the fluid at temperatures below 0°C). Some studies have addressed the impingement of water droplets containing additives relevant to fire suppression on heated surfaces (King et al. 1997; Cui et al. 2001; Manzello and Yang 2002), showing that if the additive concentration is relatively high (about 30% in mass), some differences can be observed, especially at low Weber numbers.

Other kinds of additives that are often present in liquid sprays are surface-active agents, or surfactants. Surfactant molecules adsorb to the air–water interface, positioning their hydrophilic head in water and their insoluble tails outside the solution. In doing so, they reduce the liquid surface tension. However, positioning of the surfactant molecule onto the newly created surface of an expanding water droplet takes a certain amount of time, and if the molecule is too slow it will not be effective in lowering the surface tension during drop impact events that have a duration of the order of a few milliseconds. The ability of a surfactant to reach the gas–liquid interface in a short time is described by the so-called dynamic surface tension, a property that indeed can be used to control drop impact, as shown by Zhang and Basaran (1997) and by Mourougou-Candoni et al. (1997). It must be remarked that some surfactants are believed to be relevant to fire suppression (Thames 1997), but so far their effects on drop impact phenomena have not been investigated.

A completely different class of additives is represented by flexible polymers (i.e. those polymers characterized by a high molecular mass and a low degree of branching). At rest, these molecules are coiled in order to assume a conformation of minimum energy (see for instance Strobl

1997), whereas they unfold and stretch under the action of external forces, as predicted theoretically by De Gennes (1974) and observed experimentally, for instance, by Keller and Odell (1985). The effect of flexible polymers on drop impact was first investigated by Bergeron (Bergeron et al. 1998, 2000; Bergeron and Qu  r   2001; Vovelle et al. 2001; Bergeron 2003), and independently by Crooks and Boger (2000). In particular, they observed that very tiny amounts of these additives (of the order of 0.01% in mass) can significantly increase the energy dissipation during the expansion of the lamella, causing the drop to stick to the wall without bouncing off.

The present work aims to extend such investigations on the effects of polymer additives to the impact of liquid drops on hot surfaces. In particular, the behaviour of a drop during impact on a surface heated above the saturation temperature of the liquid was observed experimentally by high-frame rate cinematography. The impact of drops of pure water was compared with that of drops of a dilute polyethylene oxide water solution (0.02% M). The results show the effect of the polymer on the phenomena of drop rebound, drop splashing, and the emission of secondary droplets.

2 Fluid characterization

The fluid used in the experiment reported in the present work was a dilute water solution of polyethylene oxide (which is also known as PEO or with the commercial name of Polyox), with a mass concentration of 200 ppm. The PEO, supplied by Sigma-Aldrich Chimie S.a.r.l. (Lyon, France) under the form of granular powder, had an average molecular weight of 4,000,000 a.m.u. and a typical density of 1,210 kg/m³. The solution was prepared by gently dissolving the polymer into a batch of ultra-pure water, where a strong vortex was created by a magnetic stirrer. This procedure prevents the formation of undissolved polymer clusters, which make the solution inhomogeneous, and at the same time avoids breaking-up of polymer chains during mixing. Similar solutions were used during the experiments reported by Bergeron et al. (2000).

Because of the very small amount of polymer, the main physical properties of the solution, such as density, shear viscosity and surface tension, are almost identical to those of pure water. The equilibrium surface tension of the solution, measured with a PocketDyne mobile bubble pressure tensiometer (Kr  ss GmbH, Hamburg, Germany), was 67.4±1 mN/m at 21.5  C, that is, almost identical to that of water (72 mN/m).

The shear viscosity was measured by means of a stress-controlled rheometer (StressTech, Rheologica Instruments AB, Lund, Sweden), equipped with a cone-plane geometry having a diameter of 55 mm and a gap angle of 0.5  . Figure 2 shows that the viscosity of the PEO solution is only slightly greater than that of pure water, and is almost constant over a large range of shear rates (from 100 to 5,000 s⁻¹).

This is very important for applications, because should the additive cause a strong increase of shear viscosity, the energy required for pumping the fluid through a pipeline would also increase. The case of PEO and other

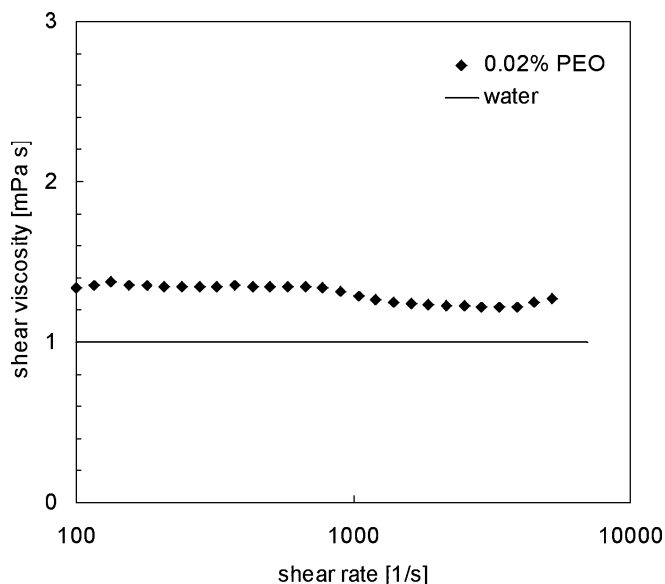


Fig. 2. Comparison between the shear viscosities of water and of the 200 ppm polyethylene oxide solution, for shear rates between 100 and 5,000 s⁻¹

polymers is peculiar in this respect, because they are also well known as turbulent drag reducing agents in wall-bounded flows (see e.g. Nieuwstadt and Toonder 2001). Moreover, because the size and the size distribution of drops in a spray strongly depend on viscosity, a change of this property often requires a new design of the nozzle as well as of the whole pumping system.

Because density, surface tension and shear viscosity do not change much, the presence of the polymer does not affect the behaviour of the solution in simple shear flow. This is no longer true in case of elongational flow, in which an elementary volume of fluid deforms under the action of the normal components of the stress tensor, as it is schematically depicted in Fig. 3a. The polymer molecules, which at rest are coiled in a minimum energy conformation, unfold under the action of normal stresses, opposing a large resistance to deformation as they are stretched.

At a molecular level, the interaction between the additive and the surrounding fluid is essentially due to hydrogen bonds between water molecules and monomers. Thus, when the polymer is coiled, the only monomers affected by the interaction are those located in the external shell, and the polymer molecule behaves like a spherical particle advected by the flow. As the velocity gradient becomes larger and larger, the polymer gets more and more stretched (De Gennes 1974) and therefore, more and more monomers become affected by the interaction with the fluid, increasing molecular friction and hence viscous dissipation.

This behaviour can be described well from a macroscopic standpoint by introducing the concept of elongational (or extensional) viscosity, the ratio of the first normal stress difference to the rate of elongation of the fluid:

$$\eta_e = \frac{\tau_{xx} - \tau_{yy}}{\dot{\epsilon}_{xx}} \quad (2)$$

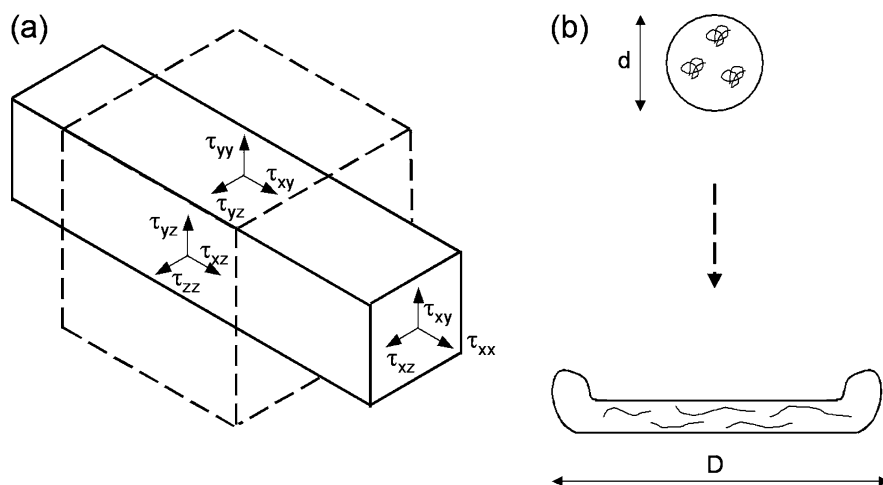


Fig. 3. Schematic representation of elongational flows: **a** deformation of an infinitesimal volume of fluid in elongational flow under the action of the normal components of the stress tensor (positive τ_{xx} , negative τ_{yy} and τ_{zz}); **b** elongational flow created during the expansion of the lamella, and unfolding of polymer molecules from a coiled conformation before impact to a stretched one after impact

For a Newtonian incompressible fluid, one can easily verify that the elongational viscosity is three times the shear viscosity. For a polymer solution the ratio η_e/η , also known as the Trouton ratio (Trouton 1906), can be of the order of 10^3 – 10^4 .

Quantitative measurements of elongational viscosity are not easy (see e.g. Macosko 1994), especially for dilute polymer solutions in low-viscosity solvents, because they require the creation of a steady-state elongational flow. It is not possible for a volume of fluid such as that represented in Fig. 3a to stretch to infinity, because it will get thinner and thinner and eventually break-up. Furthermore, the stiffness of polymer chains is not constant, but grows as they approach the maximum elongation: thus, the instantaneous values of elongational viscosity are not constant during measurements.

Measurements that reasonably approach steady state have been obtained for certain polymer solutions by means of the filament-stretching technique (Sridhar et al. 1991; Bazilevskii et al. 2001). Unfortunately, this technique is only applicable to relatively viscous liquids, as the filament breaks up too rapidly for low-viscosity samples. The alternative stagnation point devices, such as the opposed nozzle rheometer (Fuller et al. 1987), do offer a stationary flow, but the residence time of a polymer chain in the elongational flow field is typically quite short, has large statistical fluctuations and depends on the rate of elongation. Therefore, a steady-state value for the elongational viscosity is very hard to obtain. As for the PEO solution used in this work, measurements reported by Bergeron et al. (2000) suggest that the Trouton ratio is of the order of 10^2 for $100 \text{ s}^{-1} < \dot{\epsilon} < 1,000 \text{ s}^{-1}$, and of 10^3 for $\dot{\epsilon} > 1,000 \text{ s}^{-1}$.

The elongational viscosity is believed to play a major role in the dissipation of mechanical energy during the drop impact: when the drop spreads on the surface after the collision (see the sketch in Fig. 3b), one can observe a radial flow with a very strong rate of elongation, especially in the azimuthal direction. Thus, if the liquid contains sufficiently long polymer molecules, their stretching causes a large rate of energy dissipation, and as a consequence less energy is available for the retraction of the lamella and for the drop rebound. Bergeron et al. (2000) observed a much slower retraction velocity and the suppression of

rebound during drop impact on hydrophobic surfaces. To prove that this phenomenon is mainly driven by polymer stretching, and not by capillarity, they showed that when the polymer is added the capillary number evaluated during retraction does not change, provided shear viscosity is replaced by the elongational viscosity ($Ca = u_r \sigma / \eta_e$). In the same work, the effects of wetting were explicitly excluded by measuring dynamic contact angles of the drop during spreading and receding on different surfaces.

Recently, this conclusion was strongly criticized by Rozhkov et al. (2003), who studied the impact of drops of dilute PEO solutions on a very small target, so that the lamella could freely expand in air. They found no difference between the expansion and retraction velocities, and concluded that polymers have a great influence on the interaction of the lamella with the substrate at the retraction stage, changing the dynamic contact angle. This conclusion, however, appears to be somewhat arbitrary, simply because those authors compared two flows that had zero-stress and zero-velocity boundary conditions, respectively.

A detailed study of the influence of the concentration and the molecular weight of the polymer additives on this effect was recently performed by Crooks et al. (2001). In particular it was observed that the decrease of the retraction velocity is well correlated with the elongational viscosity of the polymer solution (measured by using an opposed nozzle method) over large ranges of concentration and molecular weight.

If the relationship between the retraction velocity of the lamella and the elongational viscosity seems to be well established (which allows one to rule out the effects of wetting in the case of polymer additives that do not absorb on the liquid surface), the actual physical mechanism is still far from understood. The stretching of polymer molecules must occur during the lamella expansion, when the largest rates of elongation can be observed (for a spreading velocity of the order of a few mm/ms, and a radius of a few mm, the azimuthal elongation rate is $\dot{\epsilon}_\theta = u/r \approx 10^3 \text{ s}^{-1}$), but it seems to have no dissipative effects because the expansion velocity and the maximum radius do not change, within experimental error, in the presence of the additive. However, the dissipation of mechanical energy becomes

effective only during the retraction stage, when velocity gradients are very small, so that polymer molecules should be coiled, even if the transition is subcritical, and the threshold elongation rate for recoiling is smaller than that of stretching (De Gennes 1974).

A possible solution may be found by assuming that stretching of polymer molecules does not occur instantaneously at the onset of elongational flow, but is somewhat delayed. In this way, polymer molecules would remain coiled during expansion and stretch at the very beginning of retraction, slowing down the *shear* flow caused by friction between water molecules and the monomers of the stretched polymer chain. If true, this would also explain why Rozhkov et al. (2003) did not observe any change of the retraction velocity in absence of a wall. A result supporting this conjecture was obtained by Hernández Cifre and García de la Torre (2001), who showed by means of Brownian dynamics simulations that each polymer molecule, in elongational flow, experiences the coil-stretch transition at a different time.

Another phenomenon where elongational viscosity is important is drop break-up (see Crooks and Boger 2000). This phenomenon occurs whenever the local pressure inside the drop, near the surface, exceeds the Laplace pressure (Levich 1962):

$$k \frac{\rho w^2}{2} > \frac{\sigma}{R^*} \quad (3)$$

where w denotes a characteristic velocity of the fluid inside the drop, k is a numerical coefficient and R^* denotes the local equivalent radius of curvature of the drop surface, which after impacting on the surface is no longer spherical ($1/R^* = 1/R_1 + 1/R_2$). The energy sources that can sustain fluid motion inside the drop are of course the drop kinetic energy, which acts mainly during the impact with the solid surface, but also during the free fall as a result of the interaction of the drop with the surrounding air, and heat, if the collision occurs on a hot wall. Once more, if energy dissipation caused by molecule stretching is important, much less energy will be available to inner fluid currents, so that the value of the dynamic pressure

close to the surface is low and the break-up condition given by Eq. 3 cannot be satisfied. Therefore, the threshold Weber number for splashing of a drop of polymer solution is expected to be much higher than for a drop of solvent.

3 Experimental apparatus and procedure

The experimental apparatus is schematically described in Fig. 4. Single drops were created by means of a screw-driven syringe dispenser at the tip of a metallic needle (i.d. 1 mm). The height of the system could be adjusted in order to change the impact velocity of drops. The needle was centred above the surface of a copper cylinder (height=35 mm, diameter=80 mm), electrically heated from below and with the lateral wall covered by a 25 mm thick ring of Microtherm MPS (Microtherm International Ltd, Upton Wirral, UK), an insulating material with a thermal conductivity of 0.025 W/mK. The surface was mirror polished with a chemical abrasive ensuring a roughness smaller than 0.5 μm . Temperature was measured by a thermocouple placed 0.2 mm below the centre of the upper surface of the cylinder, that is, below the point of impact of the drop. The large mass of the copper cylinder provided the system with adequate thermal inertia during the drop impact, while its high thermal conductivity allowed the temperature to be considered as constant in the area surrounding the point of collision. A high-frame rate camera (Camrecord, Photonetics GmbH, Kehl, Germany) recorded the impacts of single drops from an angle of 30° with respect to the surface. Images with a resolution of 512x512 pixels were captured at 1,000 frames per second. The camera was equipped with a 18-108/2.5 zoom lens. Magnification was kept constant throughout all experiments and lengths on the image could be calculated by comparison with a reference length.

Drops were illuminated by the diffuse light of a 100 W stroboscope (Sysmat ST 100 RE, Photonetics GmbH, Kehl, Germany) placed opposite to the camera (see Fig. 4), which was used to reduce motion blur of satellite droplets ejected away at high speed.

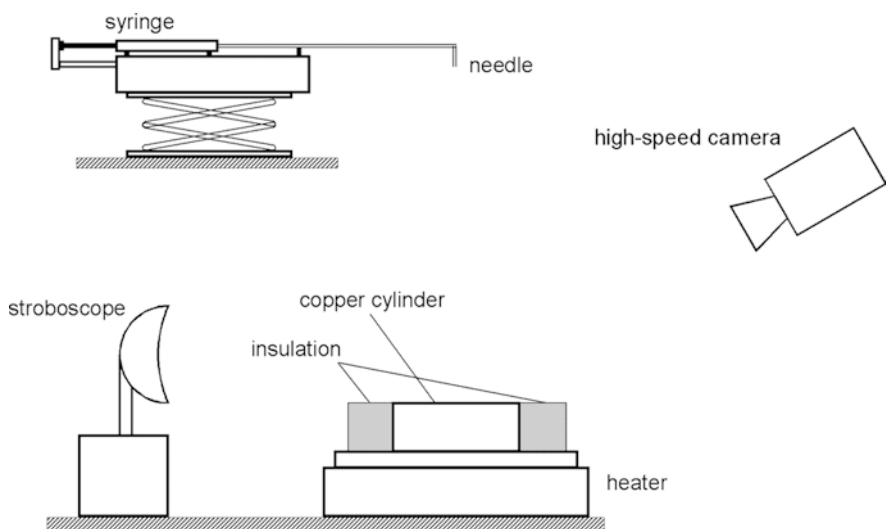


Fig. 4. Schematic description of the experimental apparatus

The drop diameter at equilibrium was obtained from drop weight measurements with a precision balance:

$$d = 3\sqrt{\frac{6m}{\rho\pi}} \quad (4)$$

Statistical measurements over 50 drops gave values of the drop diameter of 2.9 ± 0.05 mm for water and 2.8 ± 0.05 mm for the PEO solution.

The impact velocity was assumed to be equal to the free fall velocity $u = \sqrt{2gh}$ as suggested by Bernardin et al. (1997), who showed that for experiments with similar characteristics this value is in very good agreement with the actual velocity of drops measured by digital image processing. The fall heights of drops were 2.5, 7.5, 15 and 27 cm, corresponding to Weber numbers of 20, 60, 120 and 220, respectively. The Ohnesorge number was 2.2×10^{-3} for water drops and 2.9×10^{-3} for the polymer solution.

The surface temperature values ranged from 120° to 180°C , that is, above the saturation temperature of water, where the most interesting phenomena related to evaporation occur, and below the dynamic Leidenfrost temperature. In particular, in this range of temperatures, and for the lower values of the Weber number, the drop impact is often accompanied by the formation of secondary droplets, which are scattered around the main liquid nucleus during its evaporation (Rein 2003b).

During experiments, fouling of the copper surface was caused by oxidation, which was enhanced at the higher temperatures. Moreover, when drops of polymer solution were used, a thin film adhering to the surface was left after water evaporation. Therefore, a polishing liquid was used to clean the surface after each experiment.

4 Results and discussion

The image sequences describing the impact of drops and the beginning of their evaporation under different experimental conditions are shown in Figs. 5, 6, 7 and 8. In particular, each sequence follows the evolution of a drop of pure water as compared with a drop of polymer solution falling from the same height on a surface at the same temperature.

The images reported in Fig. 5 are representative of drop collisions at low speed ($We=20$). When the surface temperature is only slightly above the saturation temperature of water ($T=120^\circ\text{C}$), boiling does not occur immediately as the drop hits the surface and no thermal effect can be noticed. The polymer additive prevents the drop from bouncing off the surface by dissipating kinetic energy into polymer chain stretching, as found by Bergeron et al. (2000) for the case of drops impacting on a surface at ambient temperature.

When temperature grows ($T=140$ and 160°C), the impact of a water droplet is immediately followed by the formation of secondary droplets, which are scattered around the liquid nucleus as evaporation proceeds. One can see that the presence of the additive, even in such a small quantity, completely suppresses secondary droplets.

This can be interpreted as another effect of energy dissipation caused by the polymer. As discussed earlier, the energy required for the formation of secondary droplets must come both from the drop kinetic energy and from thermal energy supplied through the hot wall. Upon impact, they induce fluid motion inside the drop, which changes the value of dynamic pressure near the surface and eventually overcomes capillary forces. Since secondary droplets are ejected away, Eq. 3 must be modified to take into account their kinetic energy, for instance, by adding the term $\frac{\rho v^2}{2} \left(\frac{\dot{V}}{d}\right)^3$ on the RHS. If the presence of the additive damps the peaks of dynamic pressure near the drop surface, the creation of secondary droplets is inhibited.

However, the direct connection of this phenomenon with the coil-stretch transition occurring during drop impact is not evident. In fact, the emission of secondary droplets can be observed until 1 s after impact, whereas the duration of collision is only a few milliseconds. Therefore, some other dissipation mechanism caused by the polymer must be invoked and it may be, in particular, that strong velocity fluctuations inside the drop are damped by a partial stretching of polymer molecules.

For an even higher temperature of the surface ($T=180^\circ\text{C}$) one can observe that, in the case of pure water, the emission of secondary droplets occurs simultaneously to rebound, indicating that temperature is approaching the dynamic Leidenfrost value, where the drop rebounds without breaking-down. At this temperature, the polymer is still efficient in suppressing secondary droplets but, unlike in the situation described above (with $T=120^\circ\text{C}$), it has no effect on drop rebound. This happens because the physical mechanism leading to drop rebound is different. Now, the drop is pushed off the wall by the vapour film, whereas in the previous case lifting was caused by drop reshaping under the action of surface forces.

The so-called dynamic Leidenfrost phenomenon, in which drop rebound is observed when a vapour film forms between the liquid and the surface, is an intriguing subject of investigation. It is generally believed that the main cause of drop rebound is a lubrication effect of the vapour film, which reduces to zero frictional dissipation during lamella retraction. The relevance of this argument has been recently questioned by Rein (1999, 2003b), who proposed a scenario in which the vapour film plays an active role in propelling the drop off the wall.

The image sequences obtained for $We=60$ (Fig. 6) show very similar behaviour, with minor differences with respect to the sequences of Fig. 5. For $T=120^\circ\text{C}$, the rebound of the water drop is only partial, and the emission of secondary droplets for $T=140$ and 160°C is somewhat less pronounced, while it is stronger at 180°C . In all cases, the additive has the same effect as described above.

Figure 7 shows the drop behaviour for $We=120$, where one can observe that the water drop splits already into smaller drops at the temperature of 120°C . Although this looks quite similar to splashing, there is an important difference: while splashing is due to surface tension being unable to balance the kinetic energy, here the loss of continuity is rather caused by the quick evaporation of the thinnest parts of the lamella. Also, the separation occurs when the lamella is already retracting, which is known as

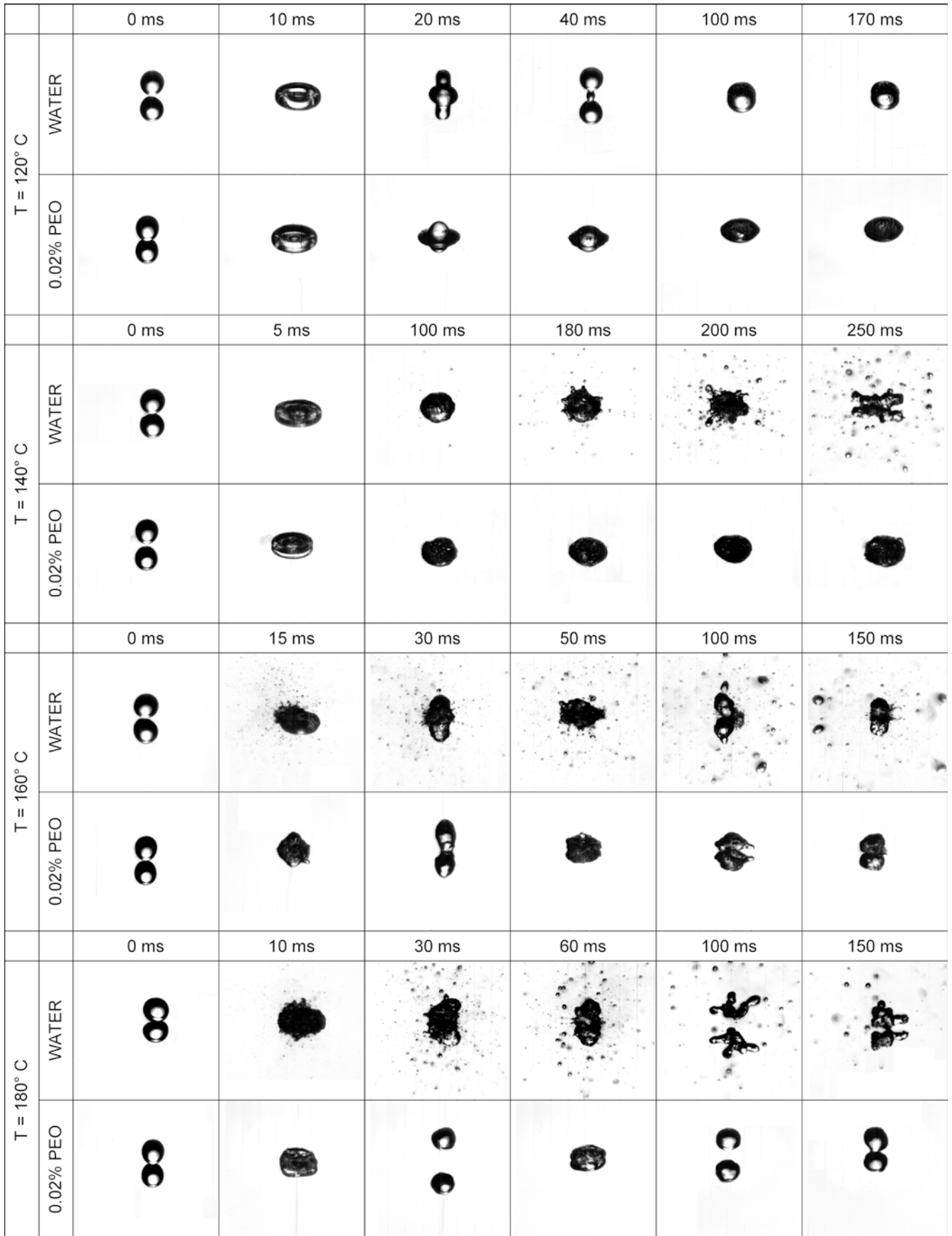


Fig. 5. Comparison between the behaviour of a drop of pure water and one of polymer solution (200 ppm PEO) during the first stages of impact ($We=20$), for different temperatures of the surface

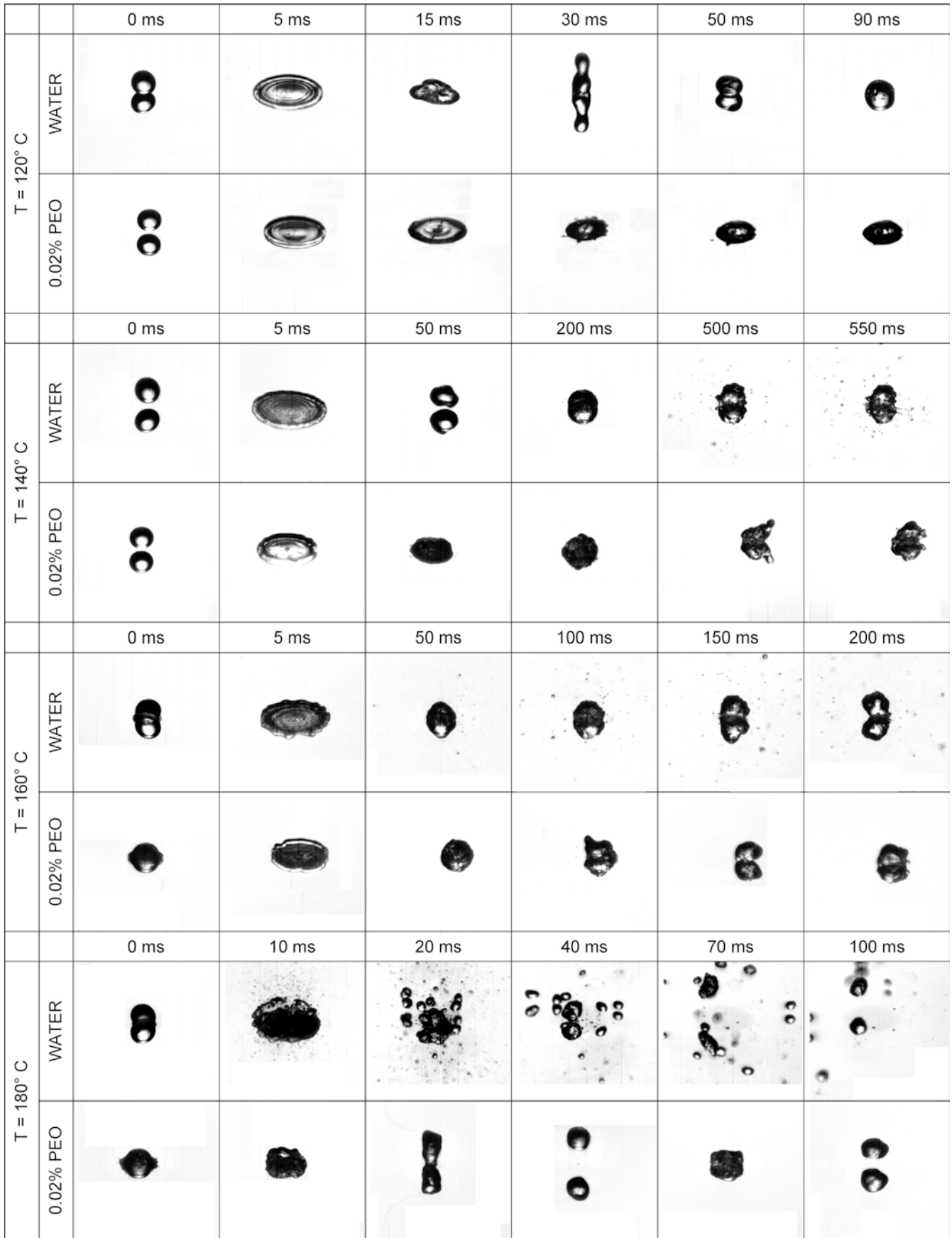


Fig. 6. Comparison between the behaviour of a drop of pure water and one of polymer solution (200 ppm PEO) during the first stages of impact ($We=60$), for different temperatures of the surface

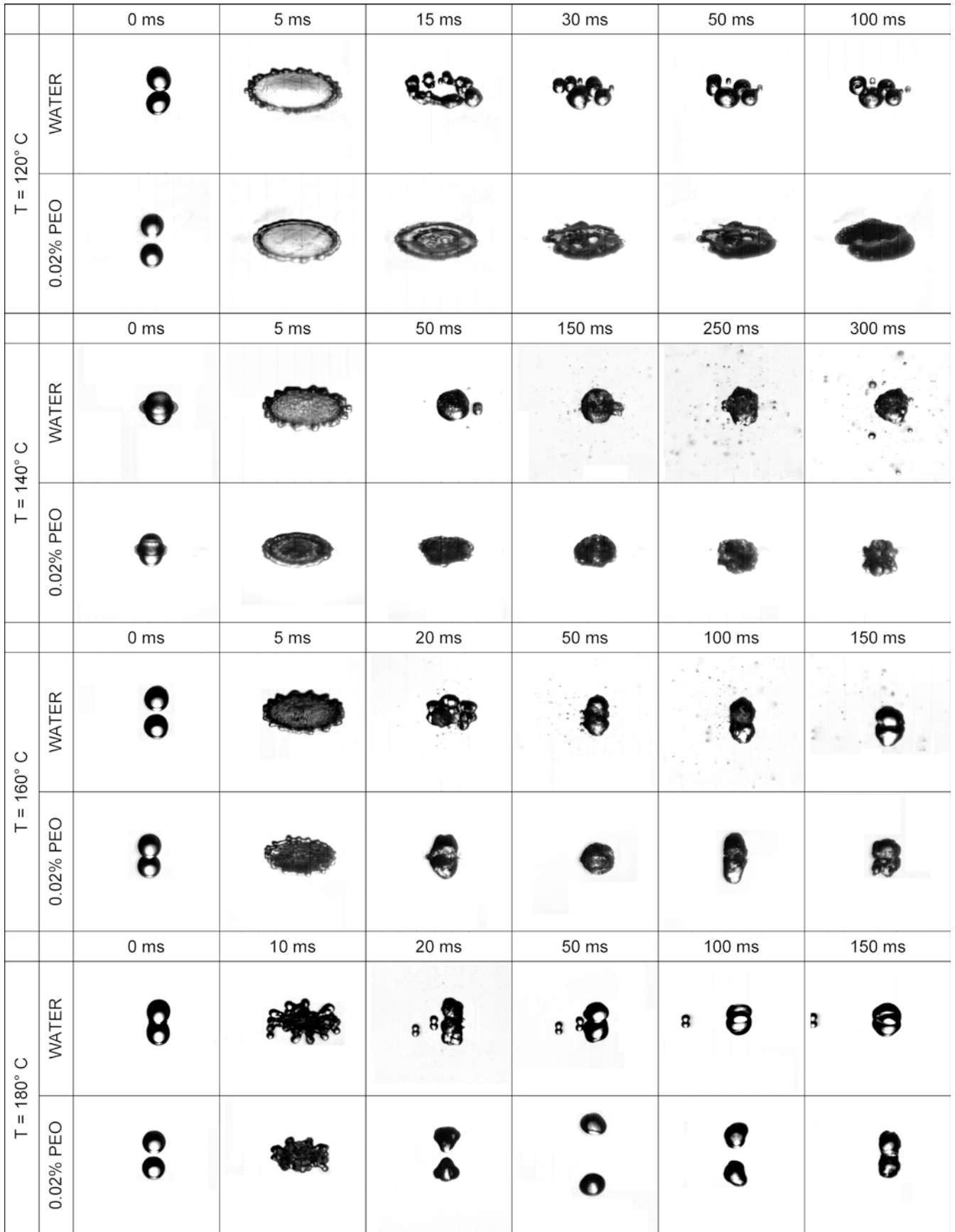


Fig. 7. Comparison between the behaviour of a drop of pure water and one of polymer solution (200 ppm PEO) during the first stages of impact ($We=120$), for different temperatures of the surface

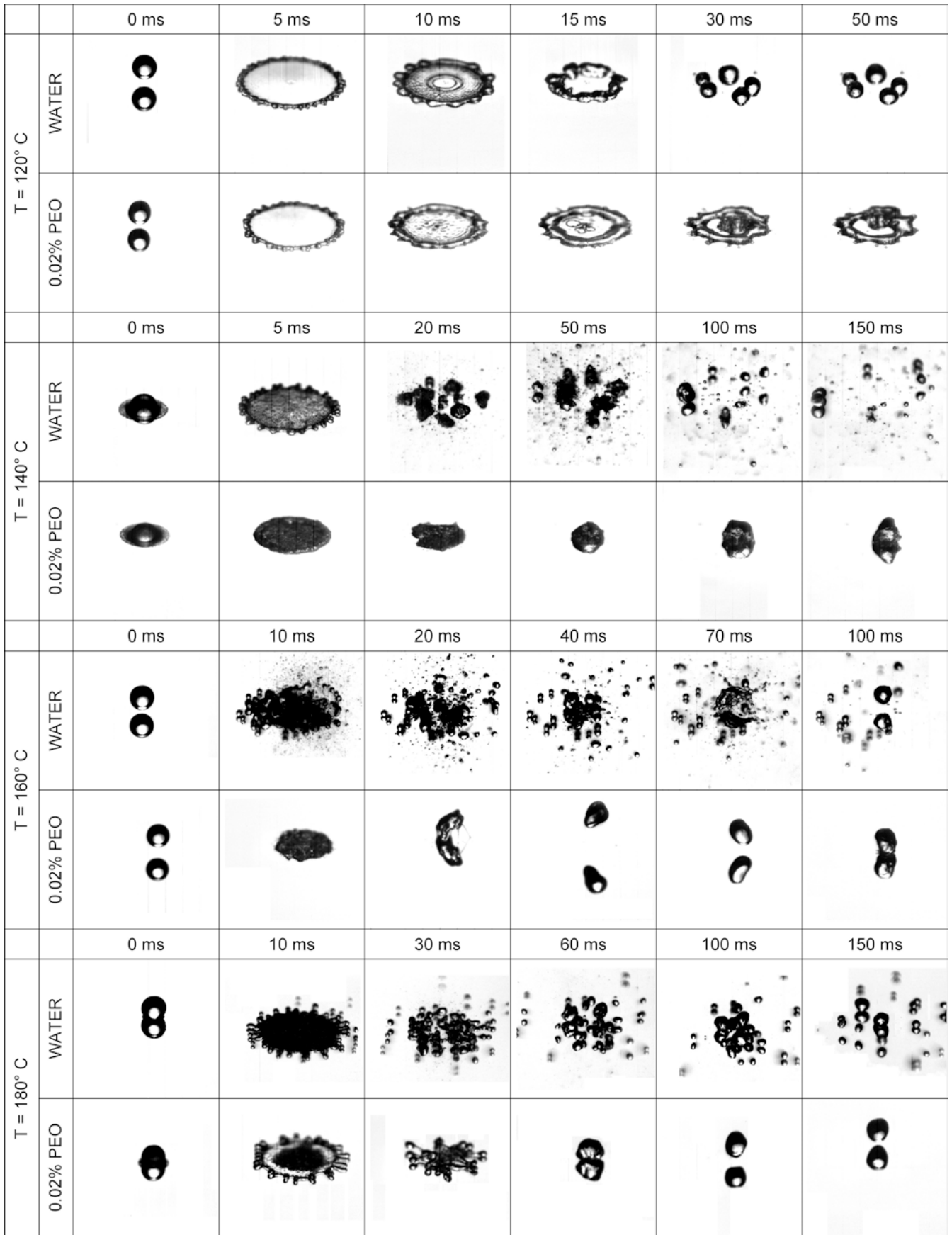


Fig. 8. Comparison between the behaviour of a drop of pure water and one of polymer solution (200 ppm PEO) during the first stages of impact ($We=220$), for different temperatures of the surface

receding break-up (Rioboo et al. 2001), and not at the maximum expansion. The velocity of smaller droplets is directed towards their centre of mass and not outwards. In this case, the effect of the polymer seems to be a slight thickening of liquid bridges, which therefore have no time to dry out completely.

Once more, mist formation can be observed for the water drop, both for $T=140$ and 160°C . At $T=180^\circ\text{C}$ the water drop does not completely disintegrate as in the previous cases at smaller Weber numbers, and only two small secondary droplets can be observed. This suggests that the dynamic Leidenfrost temperature (Rein 2003b) might have been attained.

The comparison between the two sequences at $T=180^\circ\text{C}$ show that rebound is more evident for the drop of polymer solution: thus, if the definition of dynamic Leidenfrost temperature given above holds, one can speculate that the additive causes a reduction of this quantity. As a matter of fact, this happens for lower Weber numbers as well: while at 180°C the water drop scatters secondary droplets, which means that temperature is below the dynamic Leidenfrost value, the drop of polymer solution bounces without breaking-down or scattering droplets, suggesting that the dynamic Leidenfrost temperature has been reached. Of course, a precise determination of the threshold requires more detailed experiments, which are out of the scope of this paper.

Finally, the images obtained for $We=220$ are shown in Fig. 8: the main feature is a violent bursting of the water drop, determined by the synergic action of kinetic and thermal energies. Even in this case, the additive can efficiently dissipate the energy in the liquid drop and guarantee its continuity during evaporation.

The dimensionless value of the diameter of the lamella during the first stages of the drop impact are shown in Fig. 9, for a surface temperature of 120°C . The analysis is limited to this case because the mass loss caused by evaporation is not expected to be significant, and the evolution of drops can be followed for a reasonable

amount of time before they disintegrate. The maximum spreading of drops is slightly smaller for the PEO solution, with the exception of the case of $We=20$, where it is almost identical to that of pure water. The retraction velocity of the lamella, which is given by the slope of the descending part of the curves, is considerably smaller for the polymer solution. In this case, the drop diameter slowly reaches the equilibrium value (which means that the component of the retraction velocity owing to capillary forces quickly attains a zero value), and further diameter reductions are only caused by evaporation.

5 Conclusions

The collision dynamics of a water drop containing a polymer additive on a hot surface was investigated experimentally and compared with the behaviour of a drop of pure water. Similar to what happens during the impact on cold surfaces, the polymer additive was shown to prevent drop rebound owing to the violent retraction of the lamella under the action of capillary forces. After the drop attains maximum spreading, the retraction speed of the lamella, measured by digital image processing, was found to be much slower for the solution than for the solvent, and the diameter quickly reached a stationary value. However, if the water drop rebound is propelled by the vapour layer that is created between the drop and the hot surface, when the wall temperature is above the dynamic Leidenfrost point, the additive cannot prevent the drop from bouncing off the surface.

For higher temperatures and Weber numbers, the water drop disintegrates into smaller droplets after impacting on the surface. Under the same conditions, splashing was not observed for the drop of polymer solution. The additive was also shown to inhibit the ejection of secondary droplets from the drop surface, as well as mist formation, during drop evaporation.

The quantity of polymer in the solution was so small (200 ppm) that the density and the shear viscosity were

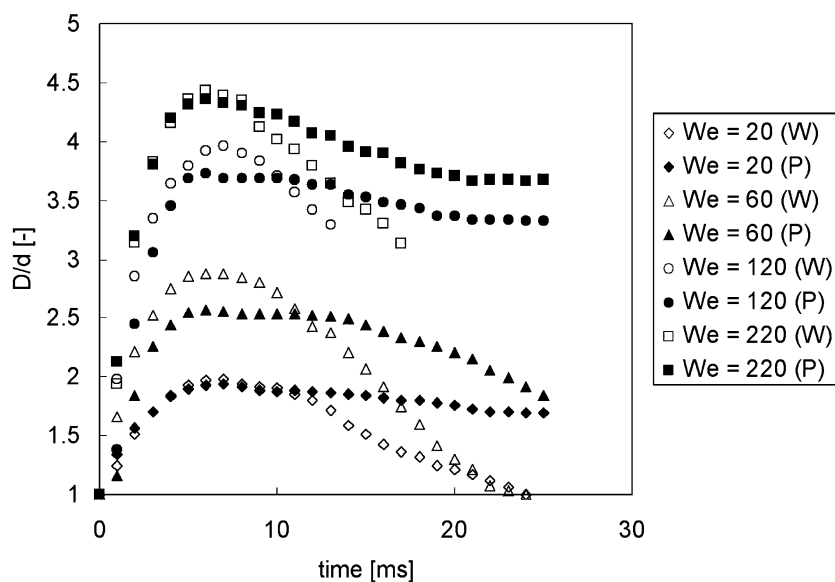


Fig. 9. Dimensionless diameter of the lamella during the first stages of impact on a copper surface at 120°C , for $We=20$ (diamonds), $We=60$ (triangles), $We=120$ (circles), and $We=220$ (squares). Open symbols refer to water drops, and filled symbols to drops of PEO solution. Data concerning water are shown until the drop rebounds or breaks down. The measurement accuracy on the lamella diameter was better than $\pm 10\%$

not affected significantly. No appreciable effects on the surface tension were observed. Therefore, all these phenomena can be attributed to the large energy dissipation caused by stretching of polymer chains in elongational flows, which occurs during the radial expansion of the lamella. In particular, this dissipation mechanism is so efficient that no energy is available for drop rebound, nor to sustain strong fluctuations of the dynamic pressure inside the drop, which lead to drop splashing or to the emission of secondary droplets. A precise quantification of this effect is not possible at present, though, because of the difficulties in measuring the elongational viscosity of diluted polymer solutions.

Finally, one can remark that if one accepts that the dynamic Leidenfrost temperature is defined as the temperature of the wall above which drop rebound occurs without breaking-down or ejection of secondary droplets, it may be speculated that polymer additives cause a reduction of this value.

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