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Research paper

Fluid dynamic and heat transfer processes between solid surfaces and non-Newtonian liquid droplets

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HIGHLIGHTS

- Dynamics and heat transfer are described for the impact of shear-thinning droplets.
- Without boiling, the shear-thinning effect is governed by the gum concentration.
- An alternative model to predict the spreading diameter is proposed.
- Thermal induced atomization is weakly dependent on the non-Newtonian viscosity.

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ABSTRACT

This paper addresses the experimental and theoretical description of the fluid dynamic and thermal behaviour of non-Newtonian (shear-thinning) droplets impacting onto smooth and micro-patterned heated surfaces. The shear-thinning liquids are mixtures of water + xanthan gum prepared with different concentrations of the gum, namely 0.05%, 0.10%, 0.15% and 0.35%wt. For droplet impacts over the surfaces heated bellow the boiling temperature of the liquid, the shear-thinning effect is clearly governed by the concentration of the non-Newtonian component, which is associated to the consistency coefficient of the constitutive model describing the viscous behaviour of the flow. In line with this, models predicting the spreading of Newtonian droplets are revisited and an alternative one is proposed, which integrates the non-Newtonian behaviour. The results suggest that heating the surface (and consequently the liquid) alters the rheology of the non-Newtonian mixture and reverses the increase of the zero viscosity, which is observed for impacts onto non-heated surfaces, thus allowing a larger spreading diameter and a significant recoiling phase for droplets with high concentrations of the non-Newtonian component. The heat transferred at droplet–surface interaction, during the spreading of the droplet is also evaluated. The analysis evidences the strong coupling between the heat transfer process and the spreading dynamics, for the non-Newtonian droplets. Further heating the surface above the boiling temperature of the liquid, the droplets impact the surfaces within the nucleate boiling regime and thermal induced atomization occurs. In this case, Phase Doppler measurements are taken to characterize the size of the secondary droplets generated within this process. The results show that the thermal induced atomization is mainly triggered by the force balance between surface tension and vapour pressure forces, so the viscosity plays a secondary role.

1. Introduction

Unlike Newtonian fluids, for which the stress tensor is a linear function of the velocity gradient and therefore the viscosity remains constant, regardless of the shear rate, in non-Newtonian fluids, the stress tensor is a generic function of the velocity gradient and of its derivatives. Usually, non-Newtonian fluids are categorized in three main groups: i) power-law (or Ostwald-De Waele) fluids, ii) yield-stress fluids and iii) viscoelastic fluids. Power law fluids are the simplest type of non-Newtonian fluids, for which the viscosity μ is simply related to the shear rate $\dot{\gamma}$ by the so-called Ostwald-De Waele equation:

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$$\mu = K\dot{\gamma}^{n-1} \tag{1}$$

Here K and n are constants of empirical nature. K is called as consistency coefficient and describes the fluid viscosity at low shear rates and matches with the Newtonian viscosity for $n = 0$. The power-law index n determines the behaviour of the fluid. Hence, the fluids are shear-thinning when $n < 1$ (i.e. the viscosity decreases with the shear rate) and shear thickening for $n > 1$. From the physico–chemical point of view, the shear thinning behaviour can be explained by the breakdown of the structure formed by interacting particles within the fluid, while the shear-thickening is often related to flow-induced jamming [1,2].

Viscoplastic (or yield-stress) fluids only flow when the applied stresses overcome a critical value (the yield stress). For applied stresses lower than the yield stress, these fluids behave like elastic solids. The simplest constitutive model describing the viscous behaviour of these fluids was proposed by Bingham [3] and introduces the shear stress component as a linear function of the velocity gradient. This intercepts at a critical value τ_c corresponding to the threshold yield point. Further improvements to the Bingham model were later proposed by Herschel–Bulkley [4] and by Papanastasiou [5]. The definition of yield-stress behaviour for a fluid instead of a solid is still a topic for discussion nowadays. More extensive reviews on this subject can be found for instance in Refs. [6–8].

Finally, in viscoelastic fluids (*e.g.* several polymer melts or solutions), part of the deformation energy is stored and released later, being the delay between energy storage and release related to a relaxation time. The main characteristic of this group of non-Newtonian fluids is the occurrence of elastic stress effects, for sufficiently high shear rates. This characteristic leads to an anisotropic application of the normal forces (*e.g.* pressure) acting on liquid finite element, contrarily to what occurs in Newtonian fluids. Pioneering work introduced by Maxwell provides the basic constitutive model for linear viscoelastic fluids. A more elaborate model and probably the most popular is the Oldroyd-B model [6–9]. More recent constitutive models have been proposed for instance by Zhu et al. [10] to describe flow induced anisotropic behaviour of viscoelastic fluids.

Non-Newtonian fluid flows are present in a variety of situations. Droplet–wall interactions are a particularly interesting flow given its interest in numerous applications, such as coating, painting or printing (*e.g.* Refs. [11–13]). Also, droplet–wall interactions involving non-Newtonian fluids are an interesting problem, from the phenomenological point of view, since they involve large spatial and temporal gradients, which will strongly alter the viscous behaviour. However, despite all the aforementioned arguments, non-Newtonian flows are studied for several decades (*e.g.* Refs. [14,15]) and droplet–wall interactions of Newtonian fluids are investigated for over a century, but the study of non-Newtonian droplets impacting onto rigid surfaces is still sparsely reported in the literature. The spreading of yield-stress (polymer) droplets over non-heated surfaces was investigated by several authors. From the various conclusions withdrawn in these studies, it is worth noting that the maximum spreading diameter decreases linearly with the yield stress magnitude (*e.g.* Refs. [16–19]). This contrasts with the power law dependence of the spreading diameter with the liquid viscosity that is usually reported for Newtonian droplets [20,21]. Most of these studies were performed for impacts onto cold and smooth surfaces. Exception is made to the work of Saidi et al. [22] who attempted to quantify the effect of the surface topography and wettability on the dynamic behaviour of yield-stress droplets. The authors also tried to determine the effect of apparent wall slip, but the results obtained were inconclusive since, as well pointed by Bertola and Marengo [2] it is impossible to distinguish between the two effects in the experiments performed by Saidi et al. [22]. Nevertheless, the results suggest a weak dependence of the maximum spreading diameter on surface wettability. The research performed on the impact of viscoelastic droplets also focus on the spreading over non-heated surfaces [23]. Some analysis of the disintegration of viscoelastic droplets was also performed in Refs. [24], but this is mainly the result of the impact onto a very small target. Most of the experimental results are also consistent in the fact that the addition of a viscoelastic component tends to preclude the occurrence of droplet rebound and/or disintegration [25], due to the strong dissipative effect occurring at the contact line.

An increasingly interest on droplet–wall interactions of non-Newtonian liquids and particularly of shear-thinning droplets is related to their relevance in various biological applications. For instance, droplet impacts of non-Newtonian preparations are the basic working principle of a method called cell printing. In this method various techniques similar to inkjet are being used to deploy living cells on a substrate to create tissue, neural cells and possibly organs (*e.g.* Refs. [26,27]). In this case, great care is necessary as the cells are extremely sensitive to shear stresses and can be easily destroyed as the droplet impacts and spreads over the surface. Similar disruptive effects have been reported in the transport of DNA samples for several years (*e.g.* Ref. [28]). Blood is a shear-thinning fluid whose behaviour is well characterized by eq. (1). Modifications of the values of the consistency coefficient K and of the power-law index n are suggested to be correlated with leukaemia [29,30].

In this context, few studies have addressed the spreading behaviour of shear-thinning droplets over smooth and cold surfaces. German and Bertola [17] and later An and Lee [31] report a significant decrease in the viscosity during spreading, which leads to a wider spreading diameter for the shear-thinning droplets, at the earlier stages after spreading. Nevertheless, the spreading diameter is generally lower for the shear thinning fluids, as a result of the higher value of the zero viscosity. German and Bertola [17] tried to relate this behaviour with the consistency coefficient K and with the power law exponent n. Their conclusions are limited to the fact that it is very difficult to change K independently from n. Nevertheless, their results suggest a dominant effect of K in the spreading, which was related to an increase of the concentration of the shear-thinning component. Based on their experimental data, An and Lee [32] adapted correlations existing in the literature to predict the spreading diameter of Newtonian droplets (devised from energy conservation principles) to their shear-thinning droplets. This adjustment was based on empirical fitting of the data combined with a re-scaling of the viscous dissipative term. Despite the modified relations reported by An and Lee [32] are well adjusted to their experimental data, they have a strong empirical nature.

Almost any information is found in the literature concerning impacts over heated and/or over rough surfaces.

Extensive investigation has been developed on droplet impacts onto heated surfaces within the various boiling regimes. The definition of the boiling regimes following the Nukyiama curve is itself a matter of investigation as it depends on the properties of the entire system, including those of the surface as, for instance surface topography, as well as on the dynamic (impact) conditions. This is particularly relevant in determining the Leidenfrost temperature, as revised for instance by Bernardin and Mudawar [33]. Hence, the heat transfer regimes for an impacting droplet are qualitatively similar to those defined in the Nukyiama curve, but significant deviations can be quantitatively observed. Numerous studies describe the morphological characteristics of the impinging droplets, many of them focussing on the spreading within the film

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