SPRAY IMPACT ON SOLID WALLS OF NON-NEWTONIAN FLUIDS, INCLUDING YIELD STRESS AND THIXOTROPIC BEHAVIOR

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Summary In a variety of applications the interactions of sprays with solid walls play an important role. The fluid may be pseudoplastic, possessing a non-vanishing yield stress, and thixotropic, with a viscosity showing a time-dependency, in addition to the shear-rate-dependency. Spray impact of thixotropic fluids with yield stress onto a dry smooth solid wall is investigated numerically. The rheological behavior of the fluids is modelled by a stationary flow curve, completed by a Quaak model for the time-dependent change of the viscosity. A commercially available code, based on the volume-of-fluid method is used. The code has been verified for fluids with yield stress and thixotropy, respectively, in viscosimetric flows and in impact processes of single drops. Calculations are performed for thixotropic fluids with yield stress of practical relevance. The results are compared with cases without thixotropy. They provide initial conditions for the subsequent evolution of the coherent fluid film.

INTRODUCTION

In a variety of applications the interactions of liquid drops and sprays with solid walls play an important role. Some of the applied fluids possess a non-zero yield stress; this behavior, characteristic for a pseudoplastic fluid, may be crucial for the impact and deposition process. In some cases the fluid viscosity shows a time-dependency in addition to the shear-rate-dependency, in such a case the fluid manifests thixotropic behavior.

The question of whether thixotropic effects have to be taken into account or not depends essentially on the ratio between the physical time scale considered, and the time scale needed by the fluid for viscosity changes to occur. If this ratio is small, thixotropic effects will not be of importance; if the ratio is large, they are expected to have a significant influence. [1] In the context of spray-wall-interactions for practically relevant fluids, this ratio is frequently small for the spray-impact itself, but becomes large for the subsequent evolution of the coherent fluid film. Thus, in view of studies of the latter, thixotropic effects have to be taken into account already for the former, since this will provide initial conditions for the subsequent evolution of the coherent fluid film. In this paper we present numerical results on the impact of sprays onto dry smooth solid walls, where the fluid concerned shows pseudoplastic and thixotropic effects.

MODELING

The fluid is modelled in its flow behavior by the flow curve for stationary shear states, which is completed by a model to account for thixotropy.

The flow curve is described by a sum of two parts; one containing the yield-stress effect and the other represented by a Cross type model with a finite dynamic viscosity η_0 at low shear rates ($\eta_0 > \eta_\infty$ or even $\eta_0 >> \eta_\infty$):

$$\tau = \tau_0 + \dot{\gamma}\eta(\dot{\gamma}), \qquad \eta(\dot{\gamma}) = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + k\,\dot{\gamma}^{1-n}} \tag{1}$$

Thixotropic effects are described here by a Quaak model, i. e. by a transport equation which describes the evolution of the apparent (total) viscosity $\eta_{ap} = \tau / \dot{\gamma}$:

$$\frac{d\,\eta_{ap}}{dt} = \frac{1}{t_R}\left(\eta_{dyn_{equ}} - \eta_{ap}\right) \text{ for } \eta_{dyn_{equ}} \geq \eta_{ap} \tag{2}$$

where t is time, t_R denotes a relaxation time, $\eta_{dyn_{equ}}$ is the equilibrium viscosity to the instantaneous shear rate $\dot{\gamma}$, according to the stationary flow curve. A similar equation as (2) holds for $\eta_{dyn_{equ}} \leq \eta_{ap}$, but with a retardation time t_r instead of t_R ; $t_r << t_R$ for the fluid considered here.

Wetting effects of the solid wall are expressed in terms of the static contact angle θ_{stat}.

NUMERICAL METHOD AND VERIFICATION OF THE NUMERICAL IMPLEMENTATION

To perform the simulations a commercially available code, Flow3D®, based on the volume-of-fluid method, has been used. The yield-stress and the shear-thinning behavior are implemented in terms of the flow curve, by expressing $\tau / \dot{\gamma}$ as a function of $\dot{\gamma}$. The flow curve is fitted to data from viscosimetry and extrapolated to very high as well as very low shear rates $\dot{\gamma}$. The time dependant thixotropic effects are implemented by equation (2) and its corresponding equation for retardation processes. Moreover a vanishing strain rate $\dot{\gamma}$ has to be avoided in numerical calculations; this is done

by prescribing a minimal value $\dot{\gamma}_c$ for the strain rate, which has to be small as compared to typical strain rates related to the spray impact process.
Capillary and wetting effects are taken into account by the static contact angle. Periodic boundary conditions are assumed in directions parallel to the wall.
The main verification of the numerical code has been carried out elsewhere [1]. To verify the yield-stress model, single drop impact has been studied for a pseudoplastic fluid without thixotropy, with a reasonable agreement between experiments and numerical calculations [2]. The verification of thixotropy effects occurs by studying rheometric flows.
The implementation of the spray data has been made by including subroutines, that were developed earlier, into the commercial code [1]. These subroutines make use of spray data obtained from experiments.

SPRAY IMPACT OF THIXOTROPIC FLUIDS EXHIBITING A YIELD-STRESS

A typical result of a spray impact calculation is shown in figure 1. The fluid is characterized by a yield stress τ_0 = 8.0 Pa. Its relaxation and retardation times are 8.5 s and 0.1 ms, respectively. Impinging drops are assumed to have an initial viscosity of 0.12 Pa s, which corresponds, in the stationary case, to a shear rate of 1000 s^{-1}. Their velocities and diameters are taken from spectra determined experimentally.
It is found that impinging drops spread along the solid wall, finally they form a connected fluid volume covering the wall. This configuration provides the initial condition for the subsequent film evolution.
On impact the drops are sheared and thus liquefied, this decrease in viscosity can clearly be recognized in figure 1. Liquefaction occurs on time scale t_r and down to a viscosity $\eta_{liq} \geq \eta_\infty$ at the most. As long as the strain rates within the individual drop impact processes are sufficient to achieve liquefaction down to essentially η_∞, the arising connected volume has roughly homogeneous viscosity, it basically relaxes as a whole on the time scale t_R. Otherwise, significant local differences in viscosity may remain, and the connected volume relaxes in a more complicated way.
In practice, thermodynamic processes like phase transitions or chemical reactions may occur on these time scales and interfere with the relaxation process.

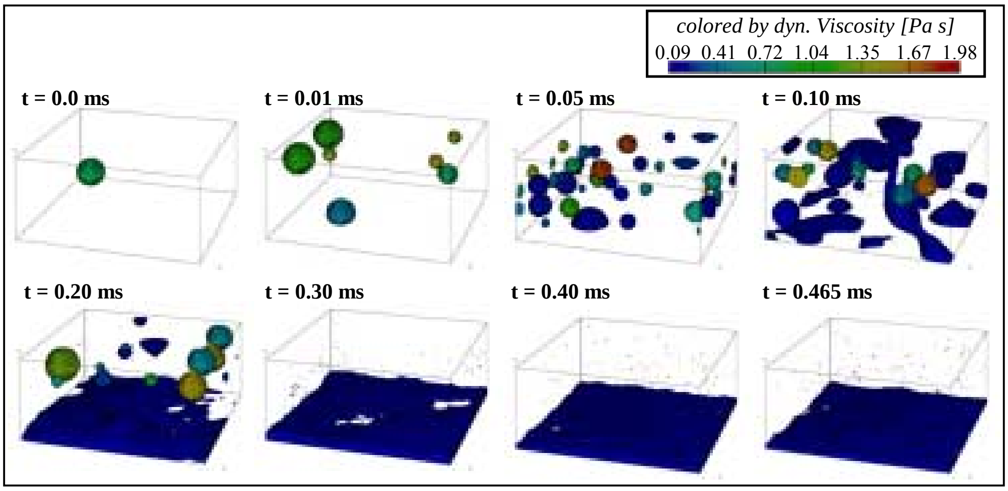

Figure 1. Spray impact and subsequent film evolution in the case of a pre-sheared thixotropic spray with a yield-stress

CONCLUSION

Spray impact for fluids with yield stress and thixotropy has been calculated numerically. It has been found that the impinging drops spread on the wall under strong shear and form a connected volume. The volume has significant local differences in viscosity or relaxes towards a more viscous state, according to whether the strain rates in the individual drop impact processes are sufficient to achieve η_∞ or not. It is therefore concluded that in practice it is crucial to know accurately the flow behavior at very high strain rates.

References

[1] Böhm C A, PhD Dissertation, Technical University of Darmstadt (D), 2002.
[2] Böhm C, Reinl A, Weiss D A, Nigen S & Binding D M, *Eurheo - 6th ECR,* Erlangen (Germany), 2002.