Spray formation with complex fluids

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Abstract. Droplet formation through Faraday excitation has been tested in the low driving frequency limit. Kerosene was used to model liquid fuel with the addition of PIB in different proportions. All fluids were characterized in detail. The mechanisms of ejection were investigated to identify the relative influence of viscosity and surface tension. It was also possible to characterize the type of instability leading to the emission drop process.

1. Introduction

The formation of spray from a liquid film on a vibrating surface is used by ultrasonic atomizers for applications ranging from humidification to metal-powder manufacturing.

However, this subject of industrial interest requires detailed knowledge of the preconditions for the formation of drops, because it is necessary to control size and conditions of the ejection.

In Faraday’s experiment, a layer of fluid in a container is excited vertically by periodic oscillation. On the flat surface, at threshold frequency and applied acceleration, instability appears in the form of parametric waves. When these control parameters (aceleration and frequency) are increased, the initial alignment of these standing-wave patterns is lost due to the appearance of secondary instabilities.

With further increased excitation, a sharp transition is observed, to a state with spikes on the surface with droplets being ejected from the tip [1]. The characteristics of the instability produced during the ejection process are analyzed here, taking into account the influence of rheology and surface tension of the fluids used to interpret the different behaviors of the system. We also test some models to check the influence of each of the variables which influence ejection.

The chosen fluids are similar to those present in fuels, with different amounts of a viscoelastic component to control the properties of the drops produced.
2. Experimental Details
The experimental system has already been described in previous publications [1]. The different components are illustrated in Fig. 1: the signal from a digital generator is amplified to excite an electromechanical transducer, which is rigidly connected to the sample cell with an aluminium bar, monitored by a speedometer with an oscilloscope. The system is completed by suitable illumination and in line computer processing.

![Experimental set-up](Image)

**Figure 1.** Experimental set-up

3. Characteristics of selected fluids
Fuel feed systems for certain types of engines are investigated for exhaust gas control (CO, NOₓ), to improve fuel efficiency in thermodynamic terms, because a non-homogeneous mixture of compounds with different vapour pressures is required.

When a viscoelastic polymer of high molecular weight is added, the physical form of hydrocarbon is altered and the size distribution of fuel droplets is narrowed [2]. Interfacial tension also increases promoting drop encapsulation and favoring simultaneous component ignition.

The rheology of the chosen components (kerosene and polyisobutilene (PIB) are represented in Fig. 2.
The rheology of the solutions employed shows “shear thinning” behaviour, preceded by a quasi-Newtonian region which corresponds to the area of interest. Also the viscosity increases with PIB concentration.

The relevant feature of this system lies in interfacial tension behavior, which grows when increasing the PIB added (cfr. Fig.3).

Figure 2. Rheology of the Kerosene + PIB solutions● Kerosene+2% PIB, * Kerosene + 1% PIB, x Kerosene + 0.5% PIB, ▲ Kerosene+0.3% PIB, ■ Kerosene+0.2% PIB. The shaded area corresponds to quasi-Newtonian behavior.

Figure 3. Interfacial tension as a function of PIB %.
4. Threshold of ejection
To identify the critical acceleration at which ejection starts acceleration was gradually increased up to the ejection of one or two droplets detected in a time span of ten seconds. Goodriges [3] proposed an expression which combines density and interfacial tension to yield a critical acceleration $a_c$

$$a_c \approx \omega_0^{4/3} \left( \frac{\sigma}{\rho} \right)^{1/3}$$  \hspace{1cm} (1)$$

where $\sigma$ stands for the interfacial tension, $\rho$ density and $\omega$ frequency. This scaling law was obtained from the dispersion relation for capillary-gravity waves and it is valid for fluids of constant viscosity.

The critical acceleration as a function of frequency is represented in Fig. 4.

![Figure 4](image-url) - Ejection acceleration threshold in terms of frequency. ♦ Kerosene +2%PIB, * Kerosene + 1%PIB, ▼ Kerosene +0.5%PIB, ● Kerosene +0.3%PIB, ▲ Kerosene +0.1%PIB, ■ Kerosene, ---- Theoretical expression (eq. 1).
Goodrige’s model (Eq.1) is represented with dotted lines in Fig. 4, jointly with our experimental results. The best fit corresponds to a Newtonian fluid (constant viscosity) and experimental $a_c$ values increase and depart from this model with increased PIB concentration.

5. Dimensionless Parameters (Newtonian fluids)
Goodriges [4] proposes dimensionless expressions for acceleration and frequency which depend on the surface tension and viscosity, which define the boundary for dominant dependence:

$$a^* = \frac{a \nu^4}{(\sigma/\rho)^3}$$

$$\omega^* = \frac{\omega \nu^3}{(\sigma/\rho)^2}$$

Dimensionless acceleration Dimensionless frequency

Depending on the values of $\omega^*$ is possible to identify the dominant influence for ejection.

viscosity dominates if $\omega^* > 10^{-5}$

surface tension dominates if $\omega^* < 10^{-5}$

These results are represented in Fig. 5

Figure 5. Dimensionless acceleration as a function of dimensionless frequency for water and different concentrations of polymer in Kerosene. ■ Kerosene, ♦Kerosene +0.1%PIB, ♦Kerosene+0.2%PIB, ◀ Kerosene+0.3%PIB, ▲ Kerosene +0.5%PIB, ● Water.
Our results match the alignment of a Newtonian liquid such as water, validating the choice of dimensionless parameters, as well as the importance of surface tension in the process.

6. Rayleigh-Plateau Instability (drops formation) and ejection mechanisms
A liquid column of capillary dimensions may be formed on the surface of the fluid where irregularities appear as control parameters are increased [5]. These irregularities mediate the formation of necks which mark the onset of the Rayleigh Plateau instability. The two possible mechanisms are illustrated in Fig. 6.

![Image of liquid columns formed with different PIB concentrations](image)

**Figure 6.** Formation of ejection tubes is more noticeable with increased PIB concentration.

The height of the capillary columns increases with PIB concentration (Fig.6), illustrating the effect on the elastic properties of the solution, because greater polymer content increases this property.

To characterize the ejection problem [6] the dimensionless Ohnesorge number Oh is used:

\[
\frac{\rho d^2 v^2}{\sigma}
\]  
(3)

The number of Weber (We)

\[
\frac{\rho d v^2}{\mu}
\]  
(4)

Reynolds (Re) number

\[
\frac{\rho d v}{\mu}
\]  
(5)

and the Ohnesorge (Oh) number

\[
Oh = \frac{\mu}{\sqrt{\rho \sigma d}} = \frac{\sqrt{We}}{Re}
\]

where \(d\) is the characteristic length scale (typically drop diameter). Ohnesorge number reflects the effect of viscosity compared with surface tension influence.
7. The column formation
The type of dripping produced directly from the surface of the liquid: with or without column formation before ejection (jetting) is represented in Fig. 7, for the Weber number as a function of Oh number.

![Figure 7](image)

**Figure 7.** Weber number as a function of Ohnesorge number for 19 g and 70 Hz in accordance with the model of Ambravaneswaran [7] □ Kerosene+5%PIB, ▲ Kerosene +0.3%PIB.

The type of ejection can be defined as simple dripping, complex dripping or jetting depending on the Weber and Ohnesorge [7, 8] dimensionless numbers. As the We value increases, the behaviour of the fluid changes from a simple dripping to a complex dripping and attains jetting when Oh is about 10-1.

In our case, the increased of the surface tension promotes the formation of a liquid column in which necks at a certain height will induce subsequent formation of droplet. The height of the capillary columns increases with a larger increased PIB content (5%).

Working at low frequencies, have access to study ejection conditions for each type of fluid and explorer different behaviors that can occur.

Critical acceleration (threshold) follows a law proportional to applied frequency to 4/3 according with Goodriges model.

As the We value increases, the behaviour of the fluid changes from a simple dripping to a complex dripping until it reaches jetting.
8. Instability: Convective or Absolute
We attempt to establish whether the observed instability can be classified as convective or absolute [9].

Starting from the neck, a droplet is ejected which may be generated above (convective instability) or above and below the neck (absolute instability). Both cases are illustrated in Fig. 8 corresponding to Kerosene + 5% PIB, 60 Hz, 19 g.

![Figure 8](image_url) Two kinds of ejection produced in the same experiment.

We have also observed that as the frequency increases, the Reynolds number decreases and the ejection departs from the absolute instability.

9. Conclusions
Working at low frequencies, it is possible to investigate ejection conditions for each type of fluid and explore various possible alternative responses. Our chosen solution increases its interfacial tension with PIB concentration.

Critical acceleration (threshold) is proportional to the 4/3 power of applied frequency, in accordance with Goodriches model. With increased We value, the behaviour of the fluid changes from simple dripping to complex dripping and finally induces jetting. Both convective and absolute instabilities could be observed in this system.
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