



Experimental investigation of magneto-rheological droplet impact on a smooth surface

Shai Rahimi, Daniel Weihs*

Faculty of Aerospace Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

We present an experimental investigation of the impact of magneto-rheological droplets on a smooth surface. The experimental setup consists of a syringe pump with capillary tube of 1.6 mm diameter located perpendicularly above a dry smooth quartz surface assembled above an electromagnetic module, which enables magnetic flux density control up to 7.8 G. Free surface flow patterns generated during the impact of droplets of 2.2 mm diameter, Reynolds number in the range 15–125 were recorded using a digital high-speed camera. The materials used in this study were commercial ferro-fluids, (hydrocarbon-based fluid containing micron-sized magnetizable particles). These fluids were characterized using a rotational rheometer modified by an electromagnetic module. The results show an up to 40% reduction in maximum spread diameters as well as reductions in spread velocities for droplets subjected to a magnetic field.

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1. Introduction

The process of droplet impact onto a rigid surface has many applications in a variety of fields and scientific disciplines such as spraying technology for agriculture, spray cooling, metallurgy and erosion of surfaces [1]. Different aspects of the process have been studied and reviewed over the last decades. Investigation of the process with emphasis on high-impact droplet velocities was conducted by Rain [2]. Under such initial conditions, fluid compressibility affects the results due to shock waves moving within the droplet. An extensive survey, considering theoretical and experimental aspects of droplet impact process onto dry surfaces and onto liquid film-wetted surfaces, has been recently published by Yarin [3].

The impact of magneto-rheological droplets on a flat surface under the influence of a magnetic field was studied by Sudo et al. [4–6]: The impact of water-based magneto-rheological droplets on a rubber surface was examined [4] by applying a magnetic field in perpendicular as well as in the tangential direction to the droplet velocity axis. It was reported that the post-impact droplet spreading diameter increases with magnetic field intensity. These findings were attributed to an increased impact pressure generated at impact zone, due to pre-impact droplet deformation caused by the applied magnetic field. In cases of droplet impact under a magnetic field applied tangential to the target surface, it was found that a liquid drop elongates along the tangential

applied magnetic field. Aerodynamic instability (splashing) was observed in the direction perpendicular to the magnetic field. A qualitative verification of the observation that a magneto-fluid droplet spreading diameter increases with an increase of applied magnetic field was reported in [5] dealing with the sequential impact of two magnetic-fluid droplets on a paper surface. Experimental investigation of the impact phenomena of kerosene-based ferri-colloid drops on target solid surfaces with different roughness was conducted in a following work [6]. They found that the maximum diameter of the impact pattern decreases with the applied magnetic field as well as with the roughness number. The impact between a magnetic fluid drop and a shallow layer of the same liquid subjected to a uniform magnetic field applied in a normal or a tangential direction to the impacted fluid free surface was studied by Bashtovoi et al. [7]. It was observed that the velocity of the circular front wave, initiated due to the droplet impact, decreases in the presence of a normal-to-surface magnetic field. In addition, a Rayleigh jet was observed after a drop impact when applying a small magnetic field normal to the surface, whereas a sharp peak and no separation of the after impact jet were observed with the growth of the magnetic field intensity.

The objective of the present study is to provide insight into the dynamic impact process of a magneto-rheological fluid droplet onto a flat surface subjected to a magnetic field. First, we found that the Carreau–Yasuda constitutive equation describes very well the rheological behavior of the magneto-rheological fluid over the investigated ranges of both shear rate and magnetic induction. Next we obtained experimentally the spread factor over time for different impact conditions and compared the experimental

* Corresponding author. Fax: +972 4 8255141.

E-mail address: dweihs@tx.technion.ac.il (D. Weihs).

Nomenclature

A	coefficient (Eq. (2))
B	magnetic induction
C_D	drag coefficient
C_v	correlation factor
D_0	impact diameter
D_S	final spread diameter
g	gravity constant
h	droplet fall distance
J	function (Eq. (5))
t	time
n	rheological parameter
$\mathbf{n}$	droplet free surface curvature
R_0	impact radius
Re	Reynolds number

V_0	impact velocity
V_{ST}	settling velocity
Z	longitudinal axis
FPS	frame-per-second
MR	magneto rheological
RMS	root-mean-square
τ_{12}	shear stress
$\dot{\gamma}$	shear rate
η	shear apparent viscosity
η_0	rheological parameter
η_∞	rheological parameter
ζ_{exp}	experimental spread factor
ζ_M	Madejski model spread factor
ρ_{air}	air density
ρ_f	fluid density

results of the final spread factor to a theoretical model [12], when fitted to the rheometrical data obtained specifically for the low-magnetic induction conditions applied in the current study.

2. Experimental setup and procedures

Fig. 1a shows a schematic layout of the experimental setup, enabling controlled and repeatable experimental parameters. The setup consists of a syringe pump connected to a 1.6 mm capillary tube generating 2.2 mm diameter droplets; an optical grade X–Y–Z table; a high-speed camera and a thin, dry and smooth quartz surface attached to an 25 Ω electromagnet.

The syringe pump was assembled perpendicularly above the impacted surface. The RMS roughness of the impacted surface, as measured by an atomic force microscope, was less than 5 nm. Droplet impact velocities (Eqs. (1) and (2)) were calculated following Range and Feuillebois [8].

$$V_0 = \sqrt{\frac{g(1 - e^{-2Ah})}{A}} \quad (1)$$

$$A = \frac{3C_D \rho_{air}}{8\rho_f R_0} \quad (2)$$

As well as Pumphrey's [9] expression (Eqs. (3)–(5)),

$$V_0 = V_{ST} \left[1 - \exp\left(\frac{-2gh}{V_{ST}^2}\right) \right] \quad (3)$$

where the droplet settling velocity and the function J are given by [10],

$$V_{ST} = \left(\frac{\mu_{air}}{\rho_{air} D_0} \right) \exp(-3.07 + 0.9935J - 0.0178J^2) \quad (4)$$

$$J = \ln[C_D(Re)^2] = \ln\left(\frac{4\rho_f \rho_{air} D_0^3 g}{3\mu_{air}^2}\right) \quad (5)$$

A commercial hydrocarbon-based magneto-fluid (Lord-Rheometrics MFR-132AD) with the density of 3090 gr/cc was used. A standard TA-Instruments CSL2-100 rotational stress-controlled rheometer was modified by an identical electromagnetic module (see Fig. 1b) to establish an empirical constitutive equation under the range of magnetic flux strength corresponding to that applied during the impact process. Standard manufacturer procedures were implemented to eliminate the air-friction parasitic moments and

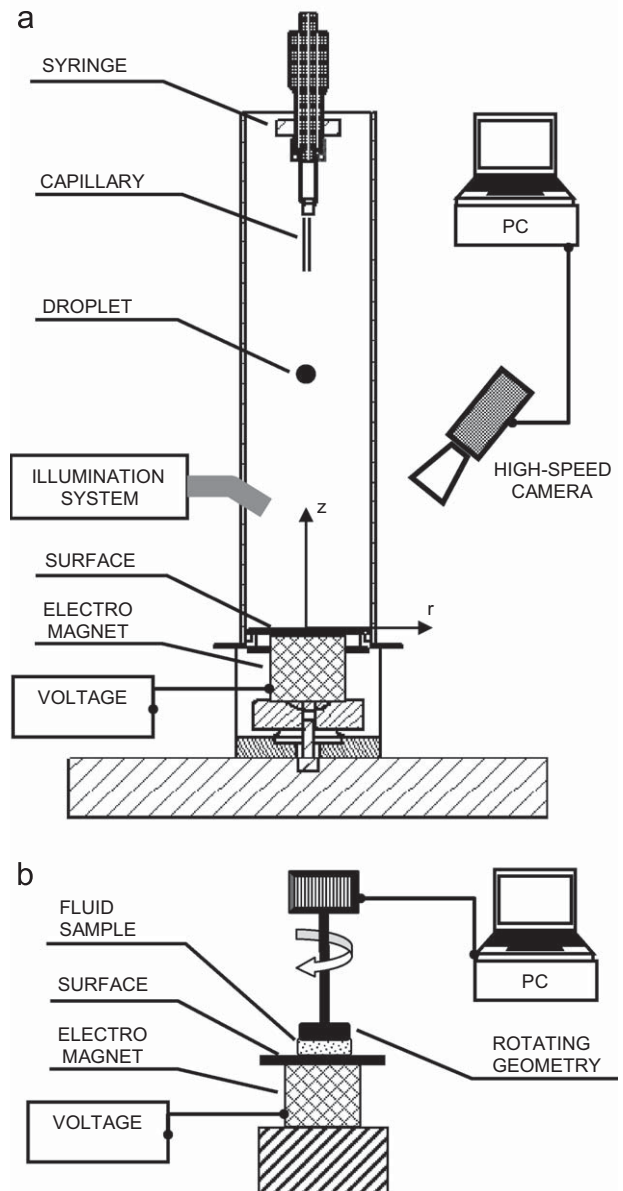


Fig. 1. Schematic diagrams of experimental setup; (a) Assembled apparatus for droplet impact surface study and (b) modified rotational rheometer.

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