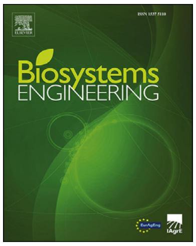
Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper

Break-up of sprayed emulsions from flat-fan nozzles using a hole kinematics model

Anthony L. Altieri [a], *Steven A. Cryer* [b,*]

[a] *Post-Doctoral Fellow, Northwestern University, McCormick School of Engineering and Applied Science, 2145 Sheridan Road, Evanston, IL 6020, USA*
[b] *DowDuPont Ag, Data Science and Informatics, Stats/Math, 9330 Zionsville Road, Indianapolis, IN 46268, USA*

ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form
1 February 2018
Accepted 8 February 2018
Published online 20 March 2018

Keywords:
Atomisation
Oil-in-water
Emulsion
Flat fan
Sheet stability
Drop size

The droplet size produced during the atomisation of agricultural liquids affects its coverage on the target and the amount off-target drift. During the spraying of emulsions using flat-fan nozzles, it has been reported that holes appear in the sprayed liquid sheet leading to its rupture. This work builds upon the hole growth and collision model presented by Altieri et al. (2014), Atomization and Sprays. 24 (8): 695–721. A model is proposed where two holes of unequal size and varying position form on the liquid sheet and grow. Upon collision, an unstable ligament between the holes ruptures and then forms a droplet. The parameter space of the model is explored by varying one parameter whilst keeping the others fixed. Parameters are then chosen randomly within a specified range to predict droplet size distributions. It was found that droplet diameter increased, and the percentage of driftable fine spray ($\leq$150 μm diameter) decreased, when the initial hole spacing was increased and the initial hole distance from the nozzle decreased. The model was compared with spray data using input parameters estimated from images of the atomisation process, yielding predictions of driftable fines with 13.1% error relative to the data. Finally, possible improvements and limitations of the model are discussed.

1. Introduction

Application of an agricultural chemical to its target is typically carried out by mixing it with water and spraying through a boom containing many flat-fan nozzles with overlapping spray patterns. Liquid is discharged as a thin continuous sheet from each nozzle orifice. The liquid sheet issuing from a nozzle is subject to instability and it subsequently disintegrates into droplets through a variety of possible mechanisms. The size distribution of the atomized droplets greatly influences how well the sprayed chemical is delivered to its target. Drops which are too large may not effectively impact on the target and may be deposited on the soil or may bounce upon impact, while drops that are too small risk being entrained in ambient air currents and carried off target forming spray drift. Fine droplets, <150 μm diameter are susceptible to drift and are often referred to as *driftable fines* (Cloeter, Qin, Patil, & Smith, 2010) although because application scenarios vary there is no agreed limit in the literature.

Liquid sheet stability and rupture has been shown to occur through various mechanisms. Altieri, Cryer, and Acharya

---

* *Corresponding author.*
E-mail address: sacryer@dow.com (S.A. Cryer).

https://doi.org/10.1016/j.biosystemseng.2018.02.006

Nomenclature

d	Distance between hole centres (e.g., hole spacing) for two hole model (mm)
D	Droplet diameter (µm)
D_j	Mean droplet diameter for bin *j* in frequency distribution
N_j	Number of droplets in bin *j* in frequency distribution
D_{90}	90th percentile for droplet diameter (µm)
D_{10}	10th percentile for droplet diameter (µm)
D_{50}	50th percentile (median) for droplet diameter (µm)
Sp	Span of droplet diameter from number distributions
DF	Percentage driftable fines based on number distribution
f_V,j	Volume fraction in bin *j in volume distribution*
VMD	Volume mean diameter (µm)
DFV	Percentage driftable fines based on volume distribution
k	Spray parameter (m^2)
r	Radial distance (m)
r_0	Initial hole radius (m)
σ	Surface tension (N m^{-1}) of sheet
ρ	Fluid density of liquid sheet
U	*x* velocity (*dx/dt*), e.g. spray speed
v	Radial velocity *dr/dt* (m s^{-1})
x_1	Distance from nozzle to centre of hole 1 (mm)
x_2	Distance from nozzle to centre of hole 2 (mm)
x_0	Distance from nozzle where a hole is formed (mm)
r_i	Radius of hole *i* (mm)
τ_j	$\tau(\xi)$ sheet thickness at centre of hole *j* (mm)
τ_N	Sheet thickness exiting nozzle (mm)
ξ	Distance from origin to leading edge of continuous liquid sheet (mm)
W_N	Width of sheet at nozzle exit (mm)
θ_n	Discharge angle of sheet (radians)
$x_2 - x_1$	Distance from centres for two colliding holes (mm)
d	Distance between colliding hole centres (mm)
x_1	Distance from nozzle to centre of hole 1 (mm) in Cartesian coordinates
x_2	Distance from nozzle to centre of hole 2 (mm) in Cartesian coordinates

(2014) provided an overview of the liquid sheet rupture literature. In some systems, where an oil phase is present in the sprayed liquid, the primary mechanism of rupture occurs through the formation of holes in the sheet. Altieri et al. (2014) presented a simple model for the mechanism of hole rupture in liquid emulsions emitted from flat-fan nozzles. In their model, two holes of equal size nucleated within the sheet at a set distance from the nozzle. Upon formation, surface tension caused the holes to expand radially until they collide. A cylindrical ligament was assumed to form at the junction of the two colliding holes, which then succumbed to the Plateau-Rayleigh instability for fluid cylinders and broke-up into droplets. The dimensionless number scaling predicted by the model was compared against experimental data.

Figure 1(a) is an image of an Interlock® (Winfield Solutions, LLC, St. Paul, MN; a proprietary agricultural adjuvant comprising of oils and surfactants for drift control) emulsion sprayed through a Teejet® (Teejet Technologies, Springfield IL) XR8002 fan nozzle. The details of the image acquisition for this and similar systems has been presented elsewhere (Altieri et al., 2014; Cryer & Altieri, 2017) and is not the focus of this work. As shown in Fig. 1(b), hole rupture mechanism can be roughly divided into four regions: 1. hole nucleation, 2. hole growth, 3. hole collision and ligament formation, and 4. ligament rupture.

1.1. *Hole nucleation*

Rupture of sprayed single-phase sheets initiates at the sheet edges under atmospheric conditions (Dombrowski & Fraser, 1954; Dorman, 1952). However, hole formation within the sheets is often observed when an oil phase is added to the spray and several possible mechanisms for hole formation have been proposed (Cloeter et al., 2010; Dombrowski & Fraser, 1954; Qin, Tank, Wilson, Downer, & Liu, 2010).

Dombrowski & Fraser, 1954 found that only hydrophobic solid and liquid particles created holes, suggesting a dewetting event occurring around the particles leading to hole formation. Cryer and Altieri (2017) investigated the analogy between sprayed sheet behaviour and foam rupture. They found that for sprayed soybean oil emulsions, larger oil droplets with diameters of similar order to the sheet thickness were more likely to develop nucleating holes, suggesting that in that system, interaction between droplets and the sheet interfaces played a role in the nucleation mechanism. They also examined data from a large study of sprayed emulsions, finding that the entry, bridging, and spreading parameters found in the anti-foaming literature were significant parameters in a regression model to predicted atomized droplet size, further suggesting that interaction of interfaces in sprayed emulsion sheets plays a key role in sheet rupture.

Other authors have found that oil droplets with diameter much smaller than the sheet thickness also can create holes. Cloeter et al., 2010; Qin et al., 2010, suggested that oil droplet deformation is responsible for hole formation. It is possible that the deformed oil drops introduce a mechanical disturbance to the sheets as they recoil. Another possibility is that, as oil droplets deform, new hydrophobic surfaces are exposed, initiating a dewetting process.

1.2. *Hole growth*

When a circular hole appears on a thin liquid sheet, surface tension acting along a hole rim generally causes it to expand. Taylor (1959) and Culick (1960) independently derived the rate of hole expansion for an inviscid liquid sheet with uniform thickness; it is typically referred to as the Taylor-Culick velocity. The effect of viscosity on hole growth for a Newtonian fluid was investigated by Savva and Bush (2009).