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# Empirical model for the maximum spreading diameter of low-viscosity droplets on a dry wall

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ABSTRACT

While many studies have explored droplet impacts using water, glycerin, or a water–glycerin mixture, few studies have investigated droplet impacts using low-viscosity fluids, such as hydrocarbons, which are commonly used in the automobile and aerospace industries. In the present study, the maximum spreading diameter of gasoline, isooctane, and ethanol droplets on an aluminum substrate was investigated. An empirical model with an accuracy of 5% error was proposed. The working fluid viscosity range was $0.45 < \mu < 1.29$ mPa s, and the droplet impact velocity range was $0.37 < V < 4.04$ m/s for a droplet diameter of 2.5 mm. The experimental ranges for the Reynolds number and the Weber number were $560 < Re < 15{,}000$ and $12 < We < 1{,}600$, respectively.

## 1. Introduction

Liquid impinging on a dry rigid substrate plays an important role in many applications, including ink-jet printing, spray coating, plasma spray coating, and spray cooling. Over the past decades, many studies have investigated different aspects of droplet impact. These studies have mainly focused on the spreading characteristics during this process, the threshold between spread and splash, and the estimation and occurrence of rebound. A comprehensive review of droplet impingement is available in Yarin [1]. Rioboo et al. [2] also classified various phenomena relating to droplet impacts. The maximum spreading diameter (or the ratio derived by normalizing the maximum spreading diameter by the diameter before impact) is a parameter of interest. Numerous studies have proposed various models that describe the spreading ratio of impacting droplets [3–24]. Most models were based on the energy balance corresponding to the pre-impact state and the state at maximum spread. Bennet and Polikakos [3], Mao et al. [4], Healy et al. [5], and German and Bertola [6] considered the wettability effect (or contact angle), while Chandra and Avedisian [7] and Pasandideh-Fard et al. [8] considered the dynamic contact angle. Yang [9], Madejski [10], Asai et al. [11] and Fukanuma and Ohmori [12] did not consider the contact angle. Son et al. [13] performed an experiment for very low Reynolds numbers (*Re*) ranging from 10 to 100 and Weber numbers (*We*) ranging from 0.05 to 2 to investigate the maximum spreading ratio ($\beta_{max} = D_{max}/D_0$) when the surface energy is comparable to the kinetic energy. Without considering the energy balance, Roisman et al. developed a model by solving the mass and momentum equations for the rim that appears at the edge of the spreading droplet [14–16]. Scheller and Bousfield [17] performed an experiment in which they increased the viscosity to 300 mPa s, and they proposed an empirical model based on their experimental data. Various other studies predicted the maximum spreading ratio based on a scaling law [18,19]. The experimental conditions from the previous studies are summarized in Table 1.

The majority of the previous studies investigating the maximum spreading ratio used droplets of water, glycerin, or a water–glycerin mixture as the working fluids. The mass ratio of water to glycerin was varied to investigate the effect of viscosity. Water-based ink and silicone oil were also used [11,20]. An and Lee [21,22] proposed a model for xanthan, which is a shear thinning fluid. However, the spreading behavior of the xanthan solutions differed from the behavior of Newtonian fluid droplets [25]. Molten tin droplets were used by other researchers, including Fukanuma and Ohmori [12] and Aziz and Chandra [23].

Despite numerous studies, few studies have focused on the maximum diameter of relatively low-viscosity droplets. Certain types of low-viscosity fluids (where low viscosity is defined as a viscosity lower than water) have an enormous role in various industries and often serve as hydrocarbon fuels. Gasoline has a relatively low viscosity value of less than 0.5 mPa s [26]. Other commonly used hydrocarbon fuels such as heptane, methanol, gasoline,

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**Table 1**
Summary of existing droplet impact studies.

| Researchers | Re | We | Working liquid | Impact velocity (m/s) | Drop size (mm) | Viscosity (mPa s) | Substrate type |
|---|---|---|---|---|---|---|---|
| Mao et al. [4] | Unnotified | Unnotified | Water, sucrose | 0.5–6 | 1.5–3.5 | 1–100 | Glass, stainless-steel, paraffin wax |
| German and Bertola [6] | 1–6889 | 1.5–213 | Water, glycerol | 0.38–2 | 3.1–3.5 | 1–925 | Parafilm-M, glass |
| Pasandideh-Fard et al. [8] | 2112 | 27 | Water, sodium dodecyl sulfate (SDS) | 1 | 2.05 | 1 | Steel |
| Chandra and Avedisian [7] | 2300 | 43 | Heptane | 1.5 | 1.5 | 0.41 | Stainless steel |
| Fukanuma and Ohmori [12] | 23,687–35,339 | 170–447 | Sn, Zn | 2.4–3.7 | 2.1–3.7 | 1.91–3.22 | $Al_2O_3$, stainless-steel |
| Asai et al. [11] | Unnotified | Unnotified | Water based ink | 2.5–20 | 0.044–0.081 | 2–7.5 | Papers, transparent film |
| Son et al. [13] | 10–100 | 0.05–2 | Water | 1 | 0.046 | 1 | Glass |
| Roisman [16] | 670–11,366 | 2–561 | Water, glycerin | 1.13–3.75 | 0.073–3.43 | 1–12 | Glass, polymer wax |
| Scheller and Bousfield [17] | 19–16,400 | 110–1115 | Water, glycerin, ethanol | 1.3–4.9 | 0.8–4 | 1–300 | Plastic film, glass |
| Rioboo et al. [20] | 20–6870 | 24–614 | Water, glycerin, isopropanol, ethanol, silicone oil | 0.78–4.1 | 1.2–4.9 | 1–925 | Glass, wax, PVC |
| Fukai et al. [24] | 3010–8800 | 56.8–364 | Water | 1.48–3.76 | 1.85–1.87 | 1 | Pyrex glass, wax |

**Table 2**
Hydrocarbons and their viscosity.

| Liquid | Viscosity (mPa s) | Liquid | Viscosity (mPa s) |
|---|---|---|---|
| n-Ethane | 0.04 | n-Dodecane | 1.49 |
| n-Propane | 0.10 | Isooctane | 0.51 |
| n-Butane | 0.17 | Ethanol | 1.2 |
| n-Hexane | 0.31 | Methanol | 0.59 |
| n-Heptane | 0.41 | Dimethyl ether | 0.13 |
| n-Octane | 0.54 | Isopropanol | 2.4 |
| n-Nonane | 0.70 | Gasoline | 0.5 |
| n-Decane | 0.91 | Diesel | 3–3.6 |

butane, and propane, also have low viscosity, mostly less than 1 mPa s, which is water's viscosity at room temperature. The viscosities of several hydrocarbon fuels are listed in Table 2 based on values from Refs. [26–28].

By changing the substrate temperature, Chandra and Avedisian [7] investigated heptane droplets colliding with a dry substrate. They also developed a maximum spreading ratio model based on the energy balance approach. However, compared with the experimental results, the model error approached 20%. This seemingly large discrepancy arose because of the underestimation of energy dissipation and because of liquid lost to evaporation in the high-temperature region. Other hydrocarbon fuels, such as methanol, diesel, and isopropanol, were studied by Šikalo et al. [28] and Zhang [29], but no prediction model was proposed for these low-viscosity liquids. For hydrocarbon droplets (particularly in the automotive industry), the ability to predict the maximum spreading ratio could be crucial for estimating the amount of fuel film generated in internal combustion engines. When fuel film is formed in an engine, this film adversely affects the fuel consumption rate [30] and causes the engine to generate unburnt hydrocarbons and particulate matter [31–33].

The object of this experimental work was to investigate the maximum spreading diameter for low-viscosity hydrocarbon droplets impinging on a solid substrate. In addition, a prediction model for the maximum spreading ratio has been proposed. The working fluids considered in the present study were gasoline, isooctane, and ethanol because of their popular uses in various industrial fields. Gasoline is a multi-component fuel, and consequently, it is difficult to develop a multi-component combustion model. Isooctane is relatively simple to model and, therefore, is often used as a surrogate for gasoline [34–36]. It should be noted that all of the experimental data were obtained under the following conditions: 1-atm surrounding pressure and room temperature.

## 2. The experiment setup

The schematic of the experimental setup used to observe droplet impacts is shown in Fig. 1. The droplets were formed in a stainless steel needle (EFD, 18 gauge, inner and outer diameters of 0.84 and 1.27 mm, respectively) using a syringe pump (KSD 100) to supply the test liquid. The impact velocity was varied by changing the release heights from 10 to 1200 mm. The release height was defined as the distance between the nozzle tip and the substrate. The free-falling droplet impacted an aluminum substrate with an average surface roughness ($R_a$) of 0.02 μm. Magnified images of each droplet impact were obtained using a high-speed camera (Vision Research Inc., Phantom 7.3) equipped with a zoom lens (1.56 μm/pixel) and a Halogen lamp (250 W) aligned with the camera. The high-speed camera (18,000 fps) was used to monitor the time evolution of the droplet impact phenomena. The camera was aimed at both a side and an oblique viewing angle to observe the droplet impact behavior.

Gasoline (from a gas station), isooctane (Sigma–Aldrich; 99.0%), and ethanol (Sigma–Aldrich; 99.5%) were used as the working fluids, and the measurements of these liquids' properties are shown in Table 3. Density, viscosity, and surface tension were measured using a density cup (50 ml, Soltec), a viscometer (LVDV-I + CP, Brookfield), and tensiometer (DCAT-11, Dataphysics), respectively. The droplet sizes were estimated according to equivalent diameter $D$ or $D_{eq}$, in Eq. (1), where $D_v$ is the diameter in the vertical dimension and $D_h$ is the diameter in the horizontal dimension. $D_v$ and $D_h$ were measured based on the droplet image acquired immediately before impact. The vertical and horizontal diameter sizes differed by less than 10%. The droplet sizes for different droplets were approximately 2.5 mm, with error and standard deviation calculated to be less than 3% and 4%, respectively. The droplet diameter was measured from fifty droplets for each working fluid. The standard deviation is defined as in Eq. (2):

$$D_{eq} = \left(D_v D_h^2\right)^{1/3} \tag{1}$$

$$\sqrt{\frac{\sum (x_i - m)^2}{N}} \tag{2}$$

where $x_i$ is the $i$th measured droplet, $m$ is the mean droplet size, and $N$ is the total number of the droplets measured.

The maximum spreading diameter was measured from the image at maximum spreading based on both the side and the oblique view. The maximum spreading diameter size deviation was less than 5% at each experimental condition. To measure the contact angle, the side-view images were used. The experimental