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Liquid ligament formation dynamics on a spinning wheel

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HIGHLIGHTS

- Liquid disintegration on a spinning wheel atomizer was investigated experimentally.
- Velocity slip between liquid film and wheel surface only significant at slow rotation.
- As a ligament grows, the trajectory of its free end resembles an involute.
- Maximum ligament length is proportional to the liquid flow rate and viscosity.
- Significant effect of end pinch-off on ligament strain rate and breakup mechanism.

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ABSTRACT

A ligament-type disintegration of liquid on a spinning wheel was investigated experimentally using photographs taken by a high-speed camera. Three different Newtonian liquids were used at various flow rates and the wheel rotational speed was varied in a wide range. Velocity slip between the liquid film and the wheel surface was found to depend primarily on wheel rotational speed and angular position, dropping to approximately 1–1.5% for sufficiently fast rotation. As a liquid ligament grows from the film, the relative pathline of its free (head) end resembles an involute. Ligament strain rate on the film was found to increase steadily until the head droplet pinch-off when a short but significant strain rate reduction was observed. At this point, ligament is rapidly decelerated in the lateral direction which may cause significant longitudinal oscillations, possibly destabilizing its growth. Strain rate then increases again until the ligament detachment from the film which is soon followed by capillary breakup into droplets. The mean ligament length at detachment was determined to increase with a rising liquid flow rate and Ohnesorge number.

1. Introduction

A spinning wheel apparatus where a stream of liquid flows onto the mantle surface of the wheel has important applications in industry, especially in the production of mineral wool and other fibers (Širok et al., 2008) and in atomization of highly viscous liquids. In case of fiber production, such device is known as a *spinning machine* or a *spinner* while in case of atomization, it can be referred to as a *spinning wheel atomizer*. In this paper, we have studied isothermal atomization of Newtonian fluids, therefore the latter term will be used from this point onwards.

A spinning wheel atomizer is a rotary-type atomizer employing centrifugal force as the main disintegration mechanism. While the fundamental operating principle is similar to the rotary atomizers with central liquid feed such as spinning discs and cups atomizers, the exact liquid film formation and disintegration mechanism is notably different (Bizjan et al., 2014). Also, there are some key advantages of a spinning wheel over other rotary atomizers. Most notably, a much larger flow rate of liquid can atomize in the ligament formation mode which is preferred as it produces droplets with a relatively narrow size distribution (Liu et al., 2012b). This is due to the fact that liquid film can be made very wide, allowing for the ligaments to form from several parallel radial planes. By using additional wheels, the atomization flow rate can be further increased by several times.

However, liquid atomization on a spinning wheel is difficult to model mathematically as it occurs as an unsteady, aperiodic and asymmetric process. For this reason, mathematical and numerical modeling of spinning wheel atomizers and spinners has so far been scarce. Westerlund and Hoikka (1989) developed a relatively simple numerical model for dynamics of continuously growing mineral wool fibers on an industrial spinning machine, but the

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hydrodynamics of ligament formation were not considered. The extent of experimental investigation of the process on this particular type of apparatus is also modest. Širok et al. (2008) formed a regression model for mineral wool fiber diameter on an industrial spinning machine where melt ligaments solidify into fibers. Bajcar et al. (2013) studied silicate melt film dynamics on a spinner wheel in the initial phase of ligament formation. Recently, Bizjan et al. (2014) formed regression models for ligament and droplet diameters of Newtonian liquids on a spinning wheel atomizer while also analyzing ligament spatial distribution on the wheel. Also, a qualitative analysis of ligament formation and disintegration was performed based on the high-speed imaging of the process.

However, to properly characterize the liquid disintegration process on spinning wheels, it is necessary to perform an in-depth study of liquid film and ligament formation and breakup dynamics. This includes phenomena such as the liquid film velocity slip against the wheel, ligament detachment from the film, head droplet pinch-off and final ligament breakup into a chain of droplets. For this purpose, we conducted an experimental study of the process by means of the high-speed camera visualization followed by the image post-processing. In addition to the process dynamics, a new characteristic parameter, namely the mean ligament length was introduced for additional quantification of the ligament formation process.

This paper is organized as follows. Section 2 provides known theoretical background to the rotary atomization mechanism and the underlying fluid dynamics. In Section 3, the experimental set-up used for our study is introduced. Section 4 presents the results of image analysis, including the description of the ligament formation and breakup process as well as the quantitative properties such as the liquid film velocity slip, mean ligament length and time-dependent kinematic properties (ligament trajectories and strain rates).

2. Theoretical background and methodology

Liquid disintegration on a spinning wheel atomizer can be divided into two main phases. In the first phase, a liquid stream falls onto the mantle surface of a spinning wheel where it is drawn in motion by the viscous and adhesive forces, forming a thin film slightly wider than the liquid stream. As the film rotates with the wheel, it gradually disintegrates to ligaments that start to form in a radial direction. At this point, the second phase begins in which the ligaments grow longer and thinner until they pinch off from the film and disintegrate in a chain of droplets (Bizjan et al., 2014).

2.1. Liquid film disintegration

Initial disintegration of liquid film to ligaments is generally agreed to occur due to the hydrodynamic instabilities that develop on the liquid film and are driven by the shear and centrifugal forces. Initial liquid film disturbances required for development of unstable waves are most likely caused by the Kelvin–Helmholtz instability (Westerlund and Hoikka, 1989) induced by velocity slip between the film and the surrounding gas as well as by fluctuations in the liquid flow rate. The main wave formation mechanism however is the Rayleigh–Taylor instability (Westerlund and Hoikka, 1989; Eisenklam, 1964) which, in case of a spinning wheel, occurs when a layer of denser fluid (i.e., the rotating liquid film) is pushed towards the lighter one (i.e., the surrounding air) by the action of centrifugal force.

According to Eisenklam (1964), unstable waves forming on the liquid film surface due to the Rayleigh–Taylor instability grow at different rates depending on their wavelength. The waves below a certain cutoff wavelength are fully damped by viscous and surface tension forces while at higher wavelengths where the centrifugal force is greater than the damping forces, the waves grow exponentially and at different growth rates. The fastest growing wave (wavelength λ_m) becomes predominant and transforms into the circumferential spacing (s) between the emerging liquid ligaments (Fig. 1) (Eisenklam, 1964). In Fig. 1, f_0 denotes the wheel rotational speed in [Hz], R the wheel radius, h the liquid film thickness and B the film width.

For a film of an inviscid or low viscosity liquid, surface tension (σ) has a predominant damping effect and λ_m can be estimated by Eq. (1) for $h \geq \lambda_m/\pi$ (Eisenklam, 1964).

$$\lambda_m = \sqrt{\frac{3\sigma}{\rho R f_0^2}} \tag{1}$$

When the liquid viscosity is so large that its damping effect on wave formation can no longer be neglected, formulations for $\lambda_m = s$ become significantly more complex. Liu et al. (2012a, 2012b) investigated ligament spacing for atomization of viscous liquids on spinning cups and supported experimental results with detailed theoretical formulations of the underlying hydrodynamic instabilities. Kamiya (1972) investigated liquid disintegration on spinning disks in ligament formation mode and also developed a mathematical model for unstable wave growth. However, as recently pointed out by Bizjan et al. (2014), the formulations for centrally fed rotary atomizers where liquid spills over the apparatus lip cannot be directly applied to spinning wheels. This is primarily due to the fact that ligament circumferential distribution on the film is highly non-uniform and that the liquid film disintegrates in a direction normal rather than parallel to its surface, allowing for ligaments to form in multiple parallel planes when the film is wide enough. For this reason, Bizjan et al. (2014) used the mean number of ligaments (N) attached to the liquid film instead of ligament spacing (s), obtaining a following power law relation:

$$N = 0.360 We^{0.433} q^{0.810} \tag{2}$$

In Eq. (2), We is the *Weber number* (Eq. (3)) and q is the dimensionless flow rate (Eqs. (4) and (5)). As Eq. (2) suggests, the number of ligaments is proportional to the Weber number and liquid flow rate.

The definitions of dimensionless numbers that have been used for characterization of liquid disintegration process in this paper are as follows. Weber number for a liquid film on a spinning wheel is defined by

$$We = \frac{\rho v_0^2 R}{\sigma} = \frac{\rho (2\pi f_0)^2 R^3}{\sigma} \tag{3}$$

The dimensionless flow rate q for a spinning wheel was first proposed by Širok et al. (2008) for an industrial mineral wool

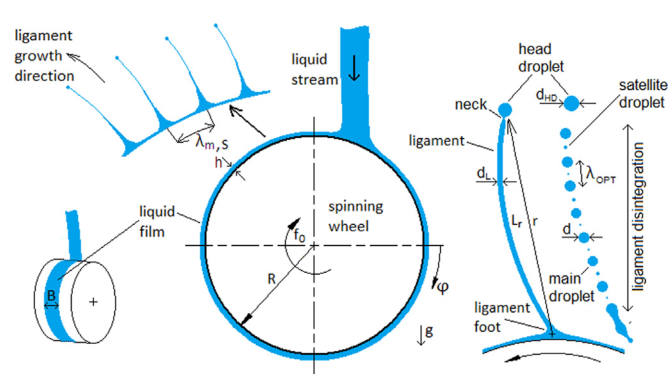

Fig. 1. Simplified presentation of ligament formation and disintegration on a spinning wheel atomizer.