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Numerical simulation of ligament-growth on a spinning wheel

Jure Mencinger[a,*], Benjamin Bizjan[b], Brane Širok[c]

[a] Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, Ljubljana 1000, Slovenia
[b] Izoteh d.o.o., Brnčičeva 15b, Ljubljana-Črnuče 1231, Slovenia
[c] Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, Ljubljana 1000, Slovenia

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ABSTRACT

Liquid ligaments can grow from perturbations in liquid film spread on a spinning wheel due to the centrifugal force acting on the film. Typically, the growth is strongly influenced by the surface tension on the evolving liquid–air interface. This phenomenon, frequently exploited in industry for the production of fibers, was investigated numerically and the Volume-of-Fluid (VOF) methodology was used to model the interface. The freely available Gerris code with adaptive mesh refinement (AMR) was used to achieve the fine resolution of the computational grid required at the evolving liquid–air interface. The results were compared with the experimental data captured by a high-speed camera. The influence of the process operating variables on the ligament growth is also presented.

Introduction

A spinning wheel atomizer, where a stream of liquid flows onto the mantle surface of the wheel (Fig. 1), is extensively used in industry for the robust disintegration of highly viscous or non-homogeneous liquids. The most common application of these kinds of rotary devices is in the production of mineral wool and other fibers (Širok et al., 2008), where liquid ligaments rise from the melt film on the wheel and solidify into fibers. Usually, 2–4 spinning wheels are used together in the so-called spinning machines or spinners, with the melt cascading between the wheels and fiberizing. Compared to other standard atomizing techniques (e.g. using spinning disc and cup atomizers), spinning wheels have several advantages. First of all, due to the large liquid film width and the possibility of using multiple spinning wheels in a single device, relatively high flow rates of liquids can be atomized or fiberized on such devices. Furthermore, rotation around the horizontal rather than vertical axis results in a less complicated set-up when liquid droplets or solidified fibers are transported by the air flow. Also, spinning wheels can be used for the fiberization of very high temperature melts (e.g. rock wool) – up to a temperature of about 1500 °C – due to the simple external geometry and large surface to volume ratio which allows for efficient cooling.

While spinning wheels have a broad range of existing and potential applications, the extent of research and modeling of these particular types of rotary devices has been scarce and mostly limited to integral time and length scales. Only recently, Širok et al. (2014) performed a high-speed camera visualization of a melt film on a wheel of an industrial spinner, analyzing the velocity and structural dynamics of the early fiberization phase. An experimental study has also been conducted recently by Bizjan et al. (2014a,2014b) on a model spinning wheel with non-solidifying Newtonian liquids being used as working media. Ligament evolution was visualized on this kind of atomization device and analyzed to form multiple regression dynamic models for characteristic ligament properties, such as the ligament number, diameter, length, and strain rate.

Some other types of rotary atomizers which, unlike the spinning wheels, incorporate a central liquid or melt influx, have been studied more extensively due to less complex boundary conditions, resulting in an easier experimental and mathematical modeling. Eisenklam (1964) formed a theoretical model for inviscid liquid ligament formation on spinning discs and cups. Kamiya (1972) improved the model to also account for viscosity effects and experimentally verified the ligament number equation on spinning discs. Eisenklam's and Kamiya's theory has been tested experimentally by many authors, recently by Liu et al. (2012a,2012b).

The fundamental hydrodynamic mechanism of liquid disintegration on spinning wheels is similar to the mechanism on spinning discs and cups as pointed out by Bizjan et al. (2014a). Generally, ligament formation on all of these types of rotary devices is driven by a centrifugal force causing the Rayleigh–Taylor hydrodynamic instability. However, the kinematics and dynamics of ligament formation on spinning wheels are significantly different and more complex than their spinning disk or cup counterparts. Ligament formation on

* Corresponding author's present address at: R&D Competence Center Cooling, Gorenje d.d., SI-3503 Velenje, Slovenia. Tel.: +386 40380064.
E-mail address: jure.mencinger@fs.uni-lj.si, jure.mencinger@gorenje.com (J. Mencinger).

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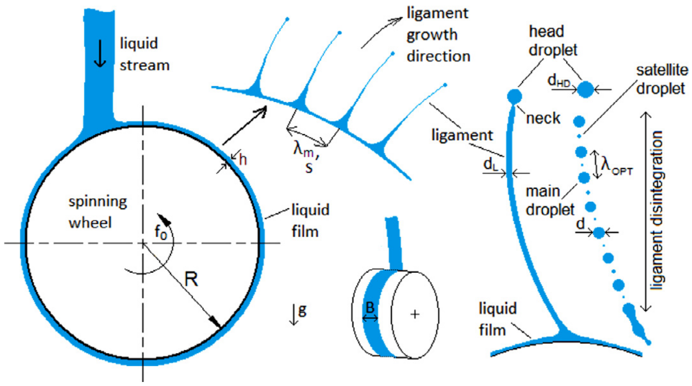

Fig. 1. Schematic (side) view of spinning wheel atomizer (left) and ligament formation/disintegration (right). [Reprinted from Bizjan et al. (2014b) with permission from Elsevier.]

spinning wheels is asymmetric and unsteady, in addition to being random, as identified by Bizjan et al. (2015), who performed a non-linear analysis of melt film velocity time series, obtained from an industrial mineral wool spinning machine. For these reasons, spinning wheel atomization and fiberization has so far mostly been modeled experimentally since analytical and numerical modeling is very complex.

While experimental modeling of the spinning wheel ligament formation mechanism has given some valuable results, such an approach faces serious limitations. First of all, the possibilities for operating parameter variations are limited by time consuming experiments and data post-processing. Also, due to safety and cost issues, experimental modeling of actual mineral melt fiberization is impractical while experimentation in an industrial environment is dictated by the plant operator and subject to many additional sources of measurement uncertainty (while the cost and safety issues still remain). Furthermore, as fiberization is a solidifying multiphase flow, some of the micro-scale ligament properties such as the local temperature and pressure distribution, though of great importance for an understanding of the fiberization process, cannot be measured by any of the currently known measurement methods. For these reasons, numerical ligament formation modeling in a computational fluid dynamics (CFD) environment is necessary for further improvements in the modeling of the process.

At this point it is necessary to mention that the numerical modeling approach is not new in the modeling of ligament dynamics and other properties. For example, Westerlund and Hoikka (1989) and Širok et al. (2008) numerically modeled cooling, kinematics and mechanical tension of ligaments. However, the ligaments were treated as cylindrical solids rigid in the longitudinal direction and ideally flexible in the transverse direction, which is not a realistic approach in the early fiberization phase when solidification has not yet occurred. On the other hand, some authors modeled ligament growth and breakup, but often without taking the heat transfer and solidification in consideration. For example, Olesen (1997) developed a numerical model for ligament breakup under the action of capillary instabilities. Tong and Wang (2007) simulated the evolution of initially still axisymmetrical ligaments in the air; they explained well the end-pinching mechanism responsible for the breakup of drops at each end of the ligament. A simulation of a jet breakup into ligaments and droplets – capturing an impressive level of details – was presented by Shinjo and Umemura (2010) who used massive computational resources with up to 5760 computational cores. The study closest to ligament fiberization was conducted by Purwanto et al. (2005) who formed a mathematical and numerical model for molten slag granulation using a spinning disk atomizer and it was also verified experimentally.

In this work, the ligament growth phase is considered and simulated numerically, starting from the imposed embryonic stage. Although the current study does not consider solidification or even heat transfer, it represents a step towards the simulations of fiberization. Already, the influence of the operating variables such as the wheel rotational speed f and film thickness h (connected with the liquid flow rate) on ligament growth can be studied. In principle, the ligament disintegration phase could also be considered. However, as shown later in the paper, an extremely high resolution of the computational mesh is required to capture this phenomena correctly; such resolution requires large computational resources even with the used state-of-the-art adaptive mesh refinement algorithm.

This paper is organized as follows. In section “Overview of the ligament-formation mechanism”, an overview of approaches to the melt fiberization mechanism is presented. The physical model consisting of the relevant equations and boundary conditions used in the present work is described in section “Physical model” along with the experimental procedure used for the verification of the simulation results. Section “Reasons to use Gerris code and its numerical solution setup” contains a brief presentation of the Gerris flow simulation code and the presentation of the used numerical solution setup. Numerical results are reported in section “Results” and conclusions are given in section “Concluding remarks”.

Overview of the ligament-formation mechanism

Fiberization is a process in which a hot liquid (melt) is scattered into ligaments which then solidify into fibers. If the liquid does not solidify, it breaks up into droplets and the process is called atomization. However, both fiberization and atomization mechanisms are similar in the initial phase when the liquid ligaments form from the annular liquid film on the wheel mantle surface.

The initial ligament formation process can be described as follows. A liquid stream of flow rate Q falls on the mantle surface of the spinning wheel with radius R. The liquid is drawn in motion by adhesion, viscous forces and surface tension (Fig. 1). A thin film of thickness h and width B is formed across the complete wheel circumference. Because of the rotation, the centrifugal force acts upon the film, pushing it radially into the surrounding air. The established unstable condition, due to the density of the liquid being much higher than the density of the air, presents Rayleigh–Taylor instability (Eisenklam, 1964). The Rayleigh–Taylor instability manifests itself in the development of the initial perturbations, which can originate from liquid feed fluctuations, from the wheel vibrations, and according to Westerlund and Hoikka (1989) also from the shear force between the melt film and the surrounding air (Kelvin–Helmholtz instability).

The growth or the decay of the perturbations at the interface of two fluids was first explained by Taylor (1950) in terms of the linear stability analysis. Depending on the wavelength, the spatial Fourier modes, proportional to $\exp(ikx)$ ($k \equiv 2\pi/\lambda$), of initial perturbation develop with different exponential growth rates $\exp(t/\tau_k)$ – each represented by time constant τ_k. The fastest growing mode, i.e. the one with the smallest possible positive value of τ_k, becomes predominant and, in the considered case, its wavelength λ_m transforms into ligament spacing s (Fig. 1). Using this approach, Eisenklam (1964) analyzed the instability of a liquid layer of thickness h, adhering to the lip of a rotating cup. He obtained the dispersion relation

$$\frac{1}{\tau_k^2} = \left[R\omega^2 - \frac{k^2\sigma}{\rho}\right] k \tanh(kh) \tag{1}$$

where R, ω, ρ, and σ denote radius at the rim of the cup, cup's angular velocity, the density of the liquid[1], and the surface tension coefficient, respectively. While the perturbation growth is accelerated by the centrifugal force, it is damped by the surface tension, as can

[1] The properties of the surrounding air are neglected due to its considerably lower density.