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The effects of nozzle geometry on waterjet breakup at high Reynolds numbers

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Abstract Waterjet breakup is traditionally considered to follow the Ohnesorge classification. In this classification, high Reynolds number waterjets are considered to atomize quickly after discharge. By generating a constricted waterjet where the water flow stays detached all the way through the nozzle, we have observed the first wind-induced breakup mode at high Reynolds numbers. Such a peculiar behavior, however, was not observed in non-constricted waterjets. Our results indicate that, constricted jets do not follow the Ohnesorge classification, in contrast to the non-constricted waterjets. We discuss the impact of nozzle geometry on the characteristics of waterjets and support our discussion by numerical simulations.

List of symbols

Z	Ohnesorge number
μ_L	water dynamic viscosity
σ	air–water surface tension
ρ_L	water density
ρ_g	air density
d_j	waterjet diameter at the nozzle outlet
d_0	nozzle capillary diameter
U_L	flow velocity
We_L	Weber number based on water density
We_g	Weber number based on air density
Re_L	Reynolds number

1 Introduction

The diversity of the liquid jet applications has led to extensive experimental and theoretical research for more than a century. In recent years, liquid jets have been studied for applications arising from two distinct industries. The first application targets an efficient atomization and the second searches for an efficient energy transfer via liquid jets. For instance, nonwovens fabric manufacturing via a process called hydroentangling is among the applications requiring energy delivery using collimated waterjets. Hydroentanglement is a process used for mechanically bonding a web of loose fibers to form uniform entangled sheets of fibers (Vahedi Tafreshi et al. 2003b). The impact of the waterjets with the fibers displaces and rotates them with respect to their neighbors. During these relative displacements, some of the fibers twist and entangle around others and inter-lock with them through fiber-to-fiber friction.

Liquid jets are known to break up somewhere downstream of the nozzle because of the interfacial forces between the jet and the surrounding air. When a liquid jet is discharged into air, disturbances on the jet surface will be augmented because of the aerodynamic interactions between the jet and the surrounding ambient. Growth of these disturbances causes the liquid column to disintegrate into droplets soon after the discharge (Lefebvre 1989). If the diameter of the droplets exceeds some critical size, they also tend to break into smaller droplets. These processes are referred to as primary and secondary breakups. Obviously, when a waterjet breaks up, its kinetic energy will be divided among many fine droplets and the jet loses its utility for an efficient energy transfer, a pre-requisite in many applications (e.g. hydroentangling or waterjet cutting).

The most commonly accepted jet disintegration classification in the fluid mechanics literature dates back to the works of Ohnesorge (1936) who combined the Reynolds and Weber numbers and proposed a dimensionless group, Z, or the so-called Ohnesorge number shown as:

$$Z = \frac{\mu_L}{\sqrt{\rho_L \sigma d_j}} = We_L^{1/2} Re_L^{-1} \qquad (1)$$

where $We_L = \frac{U_L^2 \rho_L d_j}{\sigma}$, $Re_L = \frac{\rho_L d_j U_L}{\mu_L}$, and d_j are the Weber number, Reynolds number, and the waterjet diameter at the nozzle exit, respectively. Note that for a given d_j and operating fluid, Z is a constant number. Comprehensive reviews of the jet disintegration theories are given by Reitz and Bracco (1986), Chigier and Reitz (1996), and Lin and Reitz (1998). These studies suggest that there exist four different breakup regimes for waterjets such as the one shown schematically in Fig. 1. The first regime is called the Rayleigh breakup regime. Rayleigh ignored the presence of ambient gas and liquid viscosity as well as gravity and showed a circular cylindrical liquid jet is unstable with respect to disturbances of

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