Simulating and Characterizing Water Flows Inside Hydroentangling Orifices

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ABSTRACT

The hydroentangling technique uses cone-capillary orifice nozzles to direct high-energy water jets against loose fiber webs. This study simulates the effects of orifice configuration on the water-jet properties. An axisymmetric steady-state model is considered for this two-phase system. The turbulent water jet is simulated using a realizable $k - \varepsilon$ model, and the behaviors of cone-up and cone-down geometries are investigated. The simulation reveals that the water jet produced by a cone-up orifice keeps contact with the walls all the way through the orifice and may undergo cavitation to reduce the water-jet intact length and damage to the orifice surface. In contrast, the cone-down geometry can form a constricted water jet that is enveloped by an air gap, which separates the water from the orifice surface and therefore prevents cavitation. The results are in excellent agreement with previous experimental studies.

Hydroentanglement is a process for entangling and bonding a web of loose fibers to form a uniform sheet or fabric. The underlying mechanism in hydroentanglement is exposure of fibers to a non-uniform spatial pressure field created by a successive bank of high velocity water jets. The impact of these water jets with the fibers, while they are in contact with their neighbors, displaces and rotates them with respect to their neighbors. During these relative displacements, some of the fibers twist around others and/or interlock with them due to frictional forces. The final outcome is a highly compressed and uniform fabric sheet of entangled fibers. Since its infancy, hydroentangling has shown promise for the textile industry. For a review of hydroentangling history, applications, and operating costs, see references 2, 12, 22, 23, 24, 25.

The uniformity of the product and the repeatability of the hydroentangling process require a continuous and locally uniform jet-fabric impact. Water jets are known to break up somewhere downstream of the nozzle due to the interfacial forces between them and the surrounding air. A number of parameters, including nozzle internal flow patterns resulting from cavitation and/or wall friction, influence the behavior of the water jets [11]. Cavitation refers to the condition where bubbles (made of vapor or dissolved gases) form in liquid because of the local pressure drop inside the orifice. Schmidt *et al.* visualized the cavitation in injection nozzles [16], and they demonstrated clear pictures of cavitation inside the nozzle in terms of the pressure ratio across the nozzle. The flow pattern inside the nozzle changes due to the cavitation, and that can even change the flow regime inside the nozzle [8, 11, 16, 17, 19, 20]. Water jets with a significant amount of cavitation may break up or even atomize soon after exiting the nozzle [8, 19]. Extensive cavitation may result in a constricted jet where the water is separated from the nozzle walls due to a so-called hydraulic flip [8, 19]. Note that for the hydraulic flip to occur, it is necessary to discharge the water jet into a gaseous ambient. A constricted jet may also form if the nozzle is initially filled with ambient gas (for example, air). Constricted water jets are known for having long break-up lengths. The reason seems to be the absence of cavitation or wall-induced disturbance in the water jet compared to nonconstricted jets [3, 6, 8, 19]. Broken jets have a momentum distribution varying anomalously over time and space, and they are not suitable for fabric production. Once the jet breaks up, it diverges and is no longer controllable.

Conventional hydroentangling orifice nozzles have geometries that consist of a conical part and a capillary section [3] (see Figure 1). They are called cone-up or cone-down depending on whether their inlet is the conical section or the capillary, respectively. In a recent paper, Ghassemieh *et al.* [6] reported a comprehensive study of different orifice nozzle configurations. They performed a series of experiments involving different cone-capillary combinations and concluded that the

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