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NUMERICAL SIMULATION OF THE FORMATION OF CONSTRICTED WATERJETS IN HYDROENTANGLING NOZZLES
Effects of Nozzle Geometry

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The role of nozzle geometry on the formation of constricted waterjets, waterjets that are detached from the wall throughout the nozzle, is considered in this paper. Such waterjets have found applications in various industries, including nonwoven processing. Due to the very small time and length scales involved in high-speed flow through micro-nozzles, experimental observation of the jet formation is cumbersome if not impossible. Computer simulation, on the other hand, can improve our understanding of the waterjet formation process under such conditions. In this paper, we report on flow simulations of water through sharp-edge cone-capillary nozzles having a diameter of 128 μm at different Reynolds numbers. Unsteady-state laminar two-phase flow is considered in axisymmetric nozzles with different capillary lengths. Our simulations show the separation of the flow from the nozzle wall as it enters the orifice. Simulations have also revealed that flow reattachment occurs in cases where the nozzle capillary length is longer than a critical length. For sharp-edge nozzles operating at high Reynolds numbers, the critical capillary length is found to be about 70% of the nozzle diameter. Nozzles with a capillary length less than the above critical length produce a constricted waterjet with no apparent cavitation during the jet formation.

Keywords: waterjet; flow simulation; reattachment length; hydroentangling; nonwovens.

INTRODUCTION

Hydroentangling

During the last decades, nonwoven products have shown tremendous growth. Nowadays, such fabrics can be found in a variety of industries. Examples of such applications are filtration media, wipes, hygiene products, acoustics, fire retardants and many others. The rapid growth of nonwoven products requires cost effective improvement of the involved technology. One of the most popular processes in nonwoven manufacturing is hydroentangling process. Hydroentanglement is a process used for bonding a web of loose fibres to form strong nonwoven fabrics. Hydroentangling is also known as waterjet-needling, spunlacing, hydraulic-entangling or fluid-jet needling (Rogers *et al.*, 1995). It is worth noting that fluid-jet needling includes the use of gaseous (e.g., air-jets) (USPTO classification, 2002; INNOTEX project, 2001a,b) or liquid stream for the entanglement process.

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The underlying mechanism in hydroentanglement is subjecting the fibres to a non-uniform pressure field created by a successive bank of high-velocity waterjets. The impact of the waterjets with the fibres, while they are in contact with their neighbours, displaces and rotates them with respect to their neighbours. During these relative displacements, some of the fibres twist around the others and/or interlock with them to due to frictional forces. The final outcome of this process is a strong and uniform fabric composed of entangled fibres. These structures are highly flexible, yet are very strong and outperform their woven and knitted counterparts in performance. The process is a high-speed low-cost alternative to other methods of producing fabrics. The uniformity of the product and the repeatability of the hydroentangling process require a continuous and locally uniform jet-fabric impaction. It is important that the waterjets maintain their kinetic energy downstream of the orifice for an appreciable distance. However, waterjets are known to break up somewhere downstream of the nozzle. Once a waterjet breaks up, its kinetic energy is divided among thousands of very fine droplets. Broken waterjets have practically no utility and consequently, are not able to entangle fibres efficiently. There are a number of parameters that are known for waterjet breakup, many of those originate from the nozzle itself (Lin and Reitz, 1998; Wu *et al.*, 1995; Vahedi Tafreshi and Pourdeyhimi, 2003). Hydroentangling nozzles are traditionally made up of two sections: a cylindrical section (capillary part) with a typical diameter of about 128 μm, connected to a slim cone with an angle of about 15° (see Figure 1). Hydroentangling waterjets are issued from thin-plate strips 1–6 m long having 1600–2000 orifices per metre. Manufacturing thousands of such delicate tiny orifices next to each other places many constraints on the design process. Typically, industrial jet strips have a thickness of about 1 mm, and a typical nozzle Aspect Ratio of one, $AR = 1$ (ratio of length of capillary portion to the inlet diameter). Manufacturing limitations are, in part, responsible for the cone-capillary geometry that has been used since the inception of hydroentangling some 30 years ago.

Constricted Waterjets

In the case of sharp-edge waterjet orifices, where the orifice plate separates a pressurized body of water (in a manifold) from the downstream air, flow detaches from the wall and forms a vena contracta (necking) when it enters the capillary. Depending on the length of the capillary and the hydrodynamic conditions, this flow may or may not reattach to the wall after some distance (Bayvel and Orzechowski, 1993; Lefebvre, 1989). Detached flows have peculiar characteristics that make them attractive for many applications. In the case of detached flows, there is an air gap between the liquid and the capillary wall. This air envelops the flow all the way through the capillary and does not allow any contact between liquid phase and the capillary wall. For this reason, wall-induced friction and cavitation do not disturb the structure of this flow. A waterjet resulted from a detached flow, the so-called constricted waterjet, has a higher stability and therefore, a longer breakup length (Hiroyasu, 2000; Vahedi Tafreshi and Pourdeyhimi, 2003; Anantharamaiah *et al.*, 2006). The constricted waterjets stay laminar even at remarkably high Reynolds numbers, in contrast to the non-constricted waterjets. Figure 2 shows a comparison between constricted and non-constricted waterjets issued at the same Reynolds numbers. These jets are discharged from a single hydroentangling nozzle mounted in a test device for scholarly research (Begenir *et al.*, 2004). Constricted jets are formed when the water flow enters the capillary section of the cone-capillary nozzle shown in Figure 1. The non-constricted jet is formed when water enters the nozzle from the conical side. These configurations are hereon called cone-down and cone-up, respectively. The apparently unbroken portion of the constricted waterjets shown in Figure 2(a) is not actually a continuous column. This is clearly shown in Figure 3 where the same image is shown alongside with high-speed images taken at three different locations along the jet. It can be observed that the jet consists of a continuous region [Figure 3(b)], a discrete region [Figure 3(c)], and a spray region [Figure 3(d) and (e)]. The discrete region is the region

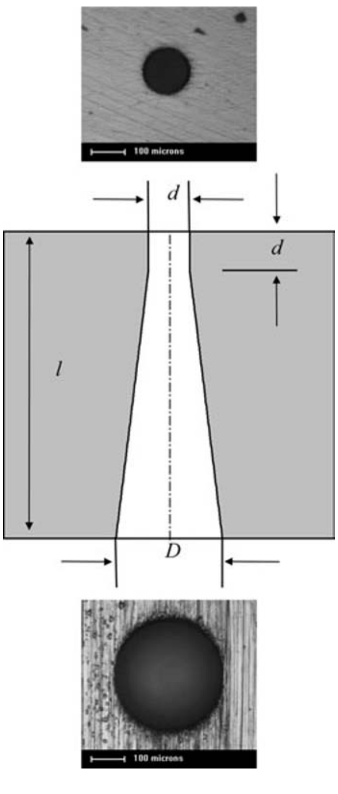

Figure 1. A typical hydroentangling orifice. Capillary diameter, $d \approx 128\,\mu m$, cone base diameter $D \approx 340\,\mu m$. Strip thickness, l, is 1 mm and $AR = 1$.

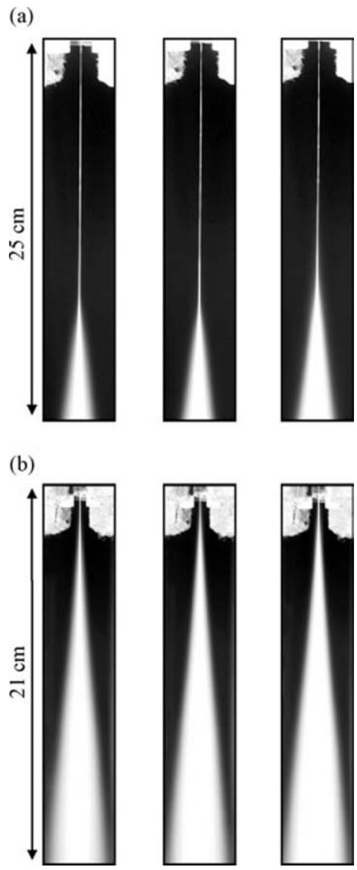

Figure 2. Constricted (a) and non-constricted (b) waterjets issued at different Reynolds numbers. From left to right, Reynolds number is 21 250, 23 900 and 26 200, respectively. Images are over-exposed to improve the contrast.