International Journal of Multiphase Flow 69 (2015) 93–101

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Experimental and numerical study on isolated and non-isolated jet behavior through centrifuge spinning system

Afsaneh Valipouri [a], Seyed Abdolkarim Hosseini Ravandi [a,*], Ahmadreza Pishevar [b], Emilian I. Părău [c]

[a] Department of Textile Engineering, Isfahan University of Technology, Isfahan 84156, Iran
[b] Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran
[c] School of Mathematics, University of East Anglia, Norwich NR4 7TJ, United Kingdom

ARTICLE INFO

Article history:
Received 3 February 2014
Received in revised form 19 June 2014
Accepted 9 October 2014
Available online 6 November 2014

Keywords:
Air-sealed centrifuge spinning
Curved liquid jet
Isolated and non-isolated liquid jet
Air drag
Navier–Stokes equations
Asymptotic expansions

ABSTRACT

This work presents a comparison between an isolated and a non-isolated curved liquid jet emerging from a rotating nozzle through centrifuge spinning system. In the centrifugal spinning process, a polymer solution has been pushed by the centrifugal force through small nozzle of a rapidly rotating cylindrical drum. Thereby thin fibers are formed and collected on a collector in the form of a web. Centrifuge spinning suffered from a strong air resistance which leads to a more deflected jet as well as its rapidly solvent evaporation resulting in thicker nanofibers. In this work, centrifuge spinning has been equipped by a rotating collector, whereas the fabrication process was skillfully sealed from ambient airflow. A comparison was drawn between the trajectory of Newtonian liquid jets fabricated by centrifuge spinning and air-sealed centrifuge spinning. The captured images of the liquid jet trajectory using a high speed camera showed that non-isolated liquid jets were more curved than isolated liquid jets due to air resistance. A pre-presented non-linear analysis of the Navier–Stokes equations was carried out and the numerical solutions were compared with the experiments. There was fairly good agreement between the isolated jet trajectory and the model-predicted one, but there were differences between the non-isolated jet trajectory and the simulation results. The non-isolated jet curved more compared to the others due to air drag. Also, the diameter of polymeric nanofibers was predicted and compared with experiments. Some qualitative agreement was found.

Introduction

Nanofibers, defined as fibers with diameters of 100–500 nm (Goddard et al., 2007), are desirable enhancements for a number of promising applications including medical textile (Vargas et al., 2010; Xie et al., 2013), filtration (Hassan et al., 2013; Cho et al., 2013; Leung et al., 2010), protective textile (Gibson et al., 2007), electronics (Rui et al., 2008), and optics (Bergshoef and Vancso, 1999).

Among the various methods used so far for producing nanofibers, such as drawing (Ondarcuhu and Joachim, 1998), template synthesis (Feng et al., 2002; Martin, 1996), and self-assembly (Liu et al., 1999), electrospinning is a well-established and intensively investigated methodology, and is currently the only known technique that can fabricate continuous nanofibres (Huang et al., 2003; Li and Xia, 2004; Fridrikh et al., 2003).

The major challenge associated with electrospinning is its production rate, compared with that of conventional fiber spinning. So far, several efforts have been made to increase the production rate of nanofibers. For instance, modified single-needle (Yamashita et al., 2007; Paruchuri and Brenner, 2007), multi-needle (Kim et al., 2006; Srivastava et al., 2007; Theron et al., 2005; Tomaszewski and Szadkowski, 2005; Vaseashta, 2007; Varesano et al., 2010, 2009 Xie and Zeng, 2012; Yamashita and Ko, 2008), needleless systems (Yarin and Zussman, 2004; Liu and He, 2007; Dosunmu et al., 2006; Jirsak et al., 2010; Wang et al., 2012; Zhou et al., 2009; Varabhas et al., 2008), a plastic filter set-up (Kumar et al., 2010) and forcespinning have been developed to enhance nanofiber production rate. Forcespinning™ or centrifuge spinning uses centrifugal force, rather than electrostatic force, as in the electrospinning process (Sarkar et al., 2010). The previous researches have indicated that applying the centrifugal force results in a significant increase in the production rate of nanofibers (Sarkar et al., 2010; Badrossamay et al., 2010). Due to centrifugal force, the polymer solution sustained by its surface tension is radially transported outward through the nozzle. There is a critical

* Corresponding author.
E-mail address: hoseinir@cc.iut.ac.ir (S.A.H. Ravandi).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.10.005
0301-9322/

rotational speed of the spinning head for which the centrifugal force finally overcomes the surface tension and the jet of the fluid is ejected from the tip of the nozzle. Centrifugal force, Coriolis force, viscous effects, and air drag are experienced by the jet in centrifuge spinning (Padron et al., 2013). The jet follows a curved trajectory due to Coriolis and drag forces. An effect of air resistance is the deflection of the jet and causes the liquid jet to progressively bend up. Another effect of air resistance is the enhancement of surface instabilities (Bellofiore, 2006). Exposing the ejected liquid jet to the high velocity airflow causes the jet to lose its solvent rapidly and as a consequence, the extension of the jet becomes more difficult, resulting in thicker nanofibers as the other effect of air resistance (Valipouri et al., 2013). It would be interested in eliminating the air resistance included in centrifuge spinning which will be discussed through the present work.

Study on the formation of droplets under rotating forces was done by Wallwork et al. (2002) and Decent et al. (2002). In their study of the prilling process for producing fertilizers, one-dimensional model equations were derived from the assumption that the flow is uniaxial and the center-line of the jet is steady at the leading order. Furthermore, a linear stability analysis of the derived inviscid model is performed in Wallwork et al. (2002) and for the viscous model in Decent et al. (2009).

Other works regarding curved liquid sheets and jets include Vanden-Broeck and Keller (1982), Entov and Yarin (1984), Dias and Vanden-Broeck (1990), Yarin (1993) and Cummings and Howell (1999). In particular, Vanden-Broeck and Keller (1982) investigated steady two-dimensional inviscid solutions with gravity, determining the trajectory of the flow, and Cummings and Howell (Vanden-Broeck and Keller, 1982) investigated nearly straight slender viscous fluid fibers arising in extrusion problems. Părău et al. (2007) presented a theoretical investigation of the effects of changing operating parameters on the break-up of curved liquid jets in stagnant air at room temperature and pressure. The Navier–Stokes equations were solved in this system with the usual viscous free-surface boundary conditions, using an asymptotic method based upon a slender-jet assumption without considering the effect of air resistance (Părău et al., 2007). However, air resistance has significant effects on liquid jet dynamic. These effects could be incorporated into the theory by including air resistance into the equations of motion. A theory to include air resistance is probably doable, but not very simple. Therefore, neglecting air resistance causes some differences between simulation and experimental results. However, reducing air resistance makes possible to neglect the effects of air resistance on liquid jet dynamic; this would be obtained in the present work. It is expected that there will be an improvement in the agreement between simulations and experimental data.

So far various one-dimensional electrospinning models have been proposed with a focus on the effects of the rheological properties of the polymer solutions on fiber formation (Carroll and Joo, 2006; Feng, 2002). Models describe all the stages of the electrospinning process using both linear and nonlinear models and incorporating the effects of solution viscosity, solvent evaporation and solidification, surface tension, and electric forces (Theron et al., 2005; Reneker et al., 2000). Some of the factors mentioned above are included in centrifuge spinning. In addition, rotational speed has significant effect on fiber formation. In current work, the effect of rotational speed on fiber morphology has been theoretically and experimentally studied.

Therefore, the first aim of this work is to introduce air-sealed centrifuge spinning for the fabrication of nanofibers. This setup has been isolated from the surrounding air using a rotating collector. In our case, air resistance is negligible because of setup isolation. In addition, a comparison is drawn between trajectory of Newtonian liquid jets as well as non-Newtonian jet fabricated by centrifuge spinning and ones fabricated by air-sealed centrifuge spinning. Images were captured of the jet trajectory using a high speed camera. Also, a non-linear analysis of the Navier–Stokes equations was carried out. The experimental results were compared to numerical solutions of equations. Further, the diameter of poly acrylonitrile (PAN) nanofibers was predicted and compared with experiments.

Materials and methods

Physical properties of liquids and solutions

The physical properties of three Newtonian fluids are given in Table 1. The trajectory of these fluids was captured during fabrication process.

Poly (acrylonitrile) (PAN) with Mn = 70,000 g/mol and Mw = 100,000 g/mol was obtained from Iran Polyacryle Co. and used as received. N,N-dimethyl formamide (DMF) from Merck was used as the solvent of PAN. PAN powder was dissolved in DMF into solution with 13 wt% concentration at ambient temperature and was gently stirred for about 24 h to prepare a homogenous solution for spinning. The viscosity and surface tension of PAN solution were measured as 784 cp and 38.44 mN/m, respectively.

Air-sealed centrifuge spinning and centrifuge spinning

Air-sealed centrifuge spinning setup is schematically shown in Fig. 1. Air-sealed centrifuge spinning setup consists of a rotating drive shaft (A), a transparent plate (B), a rotating cylindrical receptacle (C), a metallic cylindrical collector (D), and a movable transparent door (E). The rotating cylindrical receptacle holds a syringe containing polymer solution. The needle attached to the syringe has a 300 μm outer diameter with a wall thickness of 70 μm and a length of 18 mm. Polymer solution is ejected from the needle tip. The distances from the nozzle tip to the rotation center and to the collector are adjusted to 5.3 cm and 8 cm, respectively. The receptacle and the collector are firmly affixed to the drive shaft by the transparent plate. The movable transparent door is used to prevent air from entering and exiting. Hereafter, we call the collection of the receptacle, the nozzle, the collector, the transparent plate, and the movable transparent door, the head of spinning or spinning head.

Centrifuge spinning essentially consists of an axle of rotation, a cylinder to hold syringe, and a metallic cylindrical collector. The collector is stationary and does not contact to other parts of apparatus. Syringe with its holder is rotated by an axel. The difference between centrifuge spinning and air-sealed centrifuge spinning is that the collector of air-sealed centrifuge spinning is rotated by the axel and the spinning head is sealed from the air. As a result, when air-sealed centrifuge spinning is rotated, the surrounded air through spinning head rotates with the same angular velocity and the air drag force is negligible. While, when centrifuge spinning is rotated, a strong airstream is created around the nozzle. Therefore, it is expected that liquid jet fabricated by centrifuge spinning is more bent up than a liquid jet produced via air-sealed centrifuge spinning. Also, fabrication of thicker nanofibers can be

Table 1
Measured physical properties of Newtonian fluids.

Newtonian fluid	Physical properties		
	Viscosity (cp)	Density (g/cm^3)	Surface tension (N/m)
Water	1	1	0.0728
Ethanol	1.2	0.789	0.0223
Acetone	0.36	0.79	0.023